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Degree: Master of Science

Year this Degree Granted: 2001

University of Alberta

Soil Nutrient Regime Classification and Soil-Site Relationships in Aspen Stands Growing in Manitoba

By

Kenton Alan Rod

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Water and Land Resources

Department of Renewable Resources

Edmonton, Alberta

Fall 2001

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Soil Nutrient Regime Classification and Soil-Site Relationships in Aspen Stands Growing in Manitoba* submitted by Kenton Alan Rod in partial fulfillment of the requirements for the degree of Master of Science in Water and Land Resources.

ABSTRACT

To use for predicting site index in stands growing in western Manitoba, forest soil nutrient regimes were classified. Soil samples were taken from plots in the aspen and aspen-conifer mixedwood stand types. The samples were analyzed for a range of chemical and physical properties. Principle components analysis and regression analysis identified C:N ratio and forest floor mass as key variables with which soil nutrient regimes (SNR) were classified. These regimes are identifiable by field measurable traits such as root depth and humus form. Multiple regression models developed combining SNRs with soil moisture characteristics explained the most variability in aspen site index. The models improved (R^2 = 0.72) when the data were stratified by vegetation type and parent material. Based on the results of this study soil nutrient regimes were classified in the forests of western Manitoba and they were found useful in predicting aspen site index.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Steve Titus for accepting me as his student, entrusting me with this project, and for his helpful comments on this thesis. I would also like to thank Louisiana Pacific Canada Ltd. for their financial support of this project and my two field seasons at Swan River in the summers of 1999 and 2000. I hope that they find the information in this thesis useful in their future work. I received excellent advice and learned much from my committee members, Ian Corns and Bill McGill. I am also grateful to Zhiming Wang who was regularly available to offer helpful suggestions and comments. While at the university I found a great deal of support and guidance from people other than my committee. Peter Crown, Uldis Silins, and Jim Robertson were always available to give helpful advice and share their knowledge and experience with me. I hope they remember that their efforts did not go unnoticed. Noorallah Juma trusted me with teaching his soil 210 lab for three years and coordinating his soil 210 lab for one year, I feel richer for the experience, and I'm grateful to Noorallah for nominating me for the teaching award I received. Monica Molina-Ayala, Chung Nguyen, and Clive Figuereido had the biggest task of all, by putting up with a bush monkey like myself swinging through their lab. Looking back I'm sure Monica is impressed with how little glassware I actually broke, compared to what she likely thought the tally would be. There were a number of people that helped me in the lab, which was very appreciated and they include: Annette Badry, Eartha Dupuis, Paul Knaga, Edith Olson, and Mark Pederson. Loraine Bailey and Ken Rod also donated equipment, which was very useful in the collection of data for my thesis. The office staff was always great to me and it should be noted that they laughed at all my bad jokes without fail. There were many discussions and encounters with the faculty and staff that enriched my experience at the university, so many that they can't all be listed. It was definitely a learning experience.

I feel the most important part of my graduate school experience was the support of family and the discovery of new friends. My parents Ken and Marie, My brother Trevor, his wife Alyson, their children Kennady and Connor as well as my grand parents Corneluos and Cornelia Bothof were always there to remind me that there is more to life than classrooms and books. They were also quick and ready to roll their eyes at the comments that this over-educated yahoo (me) would make; thanks for keeping me grounded. At the university I also met my most important friend and partner, Vanessa Bailey. She was the best cheerleader I could have hoped for and gave both moral support and good advice during the production of this thesis. I will never forget the friends I made at the university. Warren Fleming, Darcy Henderson, Nolan Magnus, Edith Olson, Edmund Redfield, Tanja Schramm, Colin Van Bostelen, members of FOP, plus other friends that I can't mention or my thesis will become too big to fit on the shelf. A special thanks to those of you who went an extra mile to help me while I was writing my thesis abroad, notably: Edmund Redfield, Nolan Magnus, Darcy Henderson, and Thompson Nunifu. I appreciated the help and shared knowledge over the years. Some of my fondest memories were going for a coffee in SUB or a beer at RATT and talking about anything that came to mind. You guys helped make grad school an enjoyable experience beyond the books.

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LIST OF ABBREVIATIONS

FFDM forest floor dry mass (kg m^{-2})

Nutrients abbreviated in text

- Ca extractable calcium in the surface mineral soil (kg ha^{-1}; unless stated as being a forest floor variable).
- C:N carbon to nitrogen ratio of the surface mineral soil (unless stated as being a forest floor variable).
- C_{org} organic carbon of either the forest floor or the surface mineral soil.
- N_T total nitrogen of the surface mineral soil (kg ha^{-1}; unless stated as being a forest floor variable).
- P_{FF} total phosphorus in the forest floor (kg ha^{-1}).

PSP permanent sample plot

SI site index

SNR soil nutrient regime

SMR soil moisture regime

Soil drainage classes

- VR_D very rapid drainage
- R_D rapid drainage
- W_D well drained
- MW_D moderately well drained
- I_D imperfect drainage
- P_D poor drainage
- VP_D very poor drainage

Soil moisture regimes (SMR)

- MD_M moderately dry
- MF_M moderately fresh
- F_M fresh
- VF_M very fresh
- MM_M moderately moist
- M_M moist
- VM_M very moist

Soil nutrient regimes (SNR)

- VP very poor
- P poor
- M medium
- R rich
- VR very rich

Vegetation types

V-1	Balsam poplar hardwood and mixedwood
V-4	White birch hardwood and mixedwood
V-5	Aspen hardwood
V-6	Trembling aspen- Balsam fir/ mountain maple/ herb-rich
V-8	Trembling aspen- mixedwood/ tall shrub
V-9	Trembling aspen- mixedwood/ low shrub
V-13	White spruce mixedwood
V-15	Jack pine mixedwood/ shrub-rich
V-16	Jack pine mixedwood/ feather moss
V-17	Black spruce mixedwood/ shrub- and herb-rich

CHAPTER 1. INTRODUCTION

Forest harvesting operators have an obligation in Canada to stay within allowable cutting limits and a responsibility to re-grow what they cut. To help determine the allowable cut, foresters must make predictions of how much timber volume is growing, and can be grown, on the land on which they operate. A common tool for assessing the productivity of the forest is site index. Site index can be considered as an indirect measure of volume production that the land can support (Davis and Johnson 1987). This information is also useful for predicting the productivity of a location after harvest.

Site index is limited in its ability to predict productivity on locations other than single species stands (Spurr 1952). Since mixedwood forests are being logged, it is necessary to evaluate these lands by other means, one of them being soil properties. Soil properties are indirect predictors of site index (Carmean 1996). Soil properties can be evaluated somewhat independently of vegetation composition, thus they make excellent general indicators of land quality for timber growth. The soil properties that can be used to predict tree growth may differ slightly from region to region and merit investigation by forest researchers. One such property is the nutrient status of a soil. This has been researched and found to be a worthwhile factor in the prediction of site index (Klinka and Carter 1990; Klinka *et al*. 1994).

This thesis summarizes an investigation into soil nutrient regimes and soil-site relationships. The goal was to seek ways that soil properties can be used as an alternative to measuring tree height for predicting the productivity of the forested land in the study region.

1.1. Thesis objectives

The objectives of this thesis were to develop soil nutrient regimes and to model forest productivity for the Duck Mountain, Porcupine Hills region of Manitoba. The first objective was to cluster soils into classes using soil nutrients. Then the soil classes, or regimes, would be defined in terms of their unique chemical properties. Based on these

properties these groups would be sorted into those that would represent rich soil nutrients regimes and those that would represent poor. To make these nutrient regimes useful for future field crews, field identifiable traits were investigated for their ability to distinguish one soil nutrient class from another. The final objective was to test the ability of these and other soil characteristics in modeling site index. The remainder of this chapter outlines relevant theoretical background. It also includes a description of the study area and the methods and materials that were the basis for the remaining chapters.

1.2. Theoretical Background

This thesis involves the development of soil nutrient regimes and their use in modeling site index for the Duck Mountains and Porcupine Hills region of western Manitoba. This begins with a brief review of the relevant concepts: soils, site index, productivity, and the study area.

1.3. Soils and classification

1.3.1. Soil plant relationships

Parent material and climate will often promote site characteristics that are preferred by specific species. A correlation between soil parent material types and specific tree species has been found where species such as jack pine and black spruce grow on glacial fluvial deposits while white spruce and aspen grow on morainal deposits (Bridge and Johnson 1999). It is also commonly found that species such as jack pine grow on sandier well-drained parent materials while black spruce on the other hand has been found to grow on either sandy material or fine-textured soil depending on the region (Bridge and Johnson 1999; Burns and Honkala 1990). In general, black spruce grows in wetter, cooler, and often nutrient-poor environments (Van Cleve *et al.* 1983). Parent material, moisture requirements, and elevation can combine to encourage the growth of balsam poplar on flood plains (Corns 1983). Aspen with its high nutrient requirements for growth has more of an affinity for finer-textured soils though it may be found on coarse textured soils (Burns and Honkala 1990; Peterson and Peterson 1992). Although environmental characteristics play a large role in determining which species will grow at a location, there are other factors such as succession that can produce scenarios other than

the above stated trends. An example would be the shade-tolerant balsam fir growing up under the canopy and eventually replacing the original colonizing species (Burns and Honkala 1990). The height growth of the trees can depend on whether or not they are growing on sites that have properties that are conducive to the requirements of the individual species.

While soil properties can encourage the growth of certain species at particular locations, the species composition can also have an effect on the soil. Species such as white birch (*Betula papifera* Marsh.) can improve soil nutrient quality by increasing soil organic carbon and stimulating microbial activity (Bradley and Fyles 1995). In the past, spruce has been considered a soil acidifier, though there is now evidence that this acidification may be primarily due to the chemical properties of the soil rather than to the presence of the trees (Fyles and Côté 1994). Soil nutrient status and soil formation has been found to be affected by vegetative cover. An example of this is the accumulation of organic phosphorus under spruce forests in contrast to pine (Fyles and McGill 1988).

This relationship of particular locations encouraging the growth of specific species and the unique effects of different species on the soils themselves is important to this study. Knowing this one can hypothesize that given locations will have similar species compositions repeated over time, and these species will enhance the soil nutrients and/or show reflections of the soil nutrient and water status.

1.3.2. Field descriptions and sampling of soil

To use soils in predicting forest productivity, proper soil data should be collected. Field description of soils should include a description of the location as well as of the soil type. To properly describe the soil, a vertical section of the soil (a "profile") must be exposed and the soil horizons identified as described in the Canadian System of Soil Classification (Soil Classification Working Group 1998). This description of the soil includes elevation, slope, aspect, topographic position, landform, and parent material.

Undisturbed soils should be sampled by horizon (Crepin and Johnson 1993), as there is evidence that to sample by depth can mask the relationships that exist between the soil and plants (Reganold and Palmer 1995). To sample by horizon, a soil pit that exposes a vertical profile should be excavated and clean uncontaminated samples taken from the horizons. Although the ideal method for sampling undisturbed soils is by horizon, depth samples have been found effective in some studies (Kabzems and Klinka 1987; Wang and Klinka 1996). When collecting samples, soil pits should be replicated around the site to account for the spatial variability (Chen *et al*. 1998a; Monserud *et al*. 1990). This was demonstrated when Monserud (1990) suggested that soil nutrient data does not work in soil-site modeling, as there is too much variability in soils. However, it was acknowledged that the sampling techniques used in that study did not include replicates and that this shortfall may have diminished the utility of the soil information.

1.3.3. Nutrient regimes

Part of the description in forest classification can be based on soil moisture and nutrient regimes (Beckingham *et al*. 1996; Pojar *et al*. 1987). In the earlier years of forest classification in Canada these were two components identified as properties that should be evaluated (Hills 1952).

Forest soil nutrient regime classes have been established quantitatively in British Columbia and England using soil nutrient properties. Early attempts to quantify soil nutrient regimes involved the use of a combination of soil nutrients including total nitrogen, phosphorus, carbon to nitrogen ratio, pH, and extractable cations (Courtin *et al*. 1988). Since then, mineralizable nitrogen has been used to establish the nutrient regime classes in the province of British Columbia (Chen *et al*. 1998a; Kabzems and Klinka 1987; Klinka *et al*. 1994; Wang 1997). In England, similar regimes were developed using ammonium, nitrate, and ammonium plus nitrate concentrations (Wilson *et al*. 2001). In each case the soil nutrient properties were used in a cluster analysis or another ordination technique to establish the classes.

To identify the nutrient classes in the field, analyses need to be linked to field identifiable properties. One common property is that of forest floor classification, where humus forms such as mor are indicators of poorer soils, moders as medium soils, and mulls as richer soils (Beckingham *et al.* 1996; Pojar *et al.* 1987; Wilson *et al.* 2001). Other soil properties that are good indicators of nutrient regime are soil texture, coarse fragment content, presence of an Ae horizon, and presence of an Ah horizon (Beckingham *et al.* 1996; Klinka *et al.* 1994).

These nutrient regimes can then be used to predict site index. Nutrient regimes that were developed in British Columbia were found to predict site index of coastal Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) with an R^2 of up to 0.84 when combined with soil moisture regimes (Klinka and Carter 1990). In the interior of British Columbia, models were produced with soil nutrient regimes that predicted Englemann spruce (*Picea engelmannii* Parry ex Engelmann) site index with an R^2 of 0.52 and that predicted sub alpine fir (*Abies lasiocarpa* [Hook.] Nutt.) site index with an R^2 of 0.41 (Chen *et al.* 1998a).

1.4. Site Index

1.4.1. What is site index?

Site index is the most widely used estimator of forest productivity in North America. It is a measure of how well a stand can grow at a location. Site index is a measure of stand height, of a selected species, usually the dominant species in the stand, at a reference age. The reference age, or base age, has in the past been established as anything from 25-100 years though the use of 50 years is now common practice in North America (Corns and Pluth 1984; Curt 1999; Huang 1994; Monserud *et al.* 1990). The base age chosen for a species site index is dependent on the average lifespan or rotation age of the species (Avery and Burkhart 1994). For the purposes of this paper site index will be the height of dominants and co-dominants of a stand at base age 50 years unless stated otherwise.

In the past the height that was predicted was total height. A change that has arisen during the evolution of site index is the use of breast height age instead of total age, for the

reference age (Carmean and Lenthall 1989; Cieszewski and Bella 1993; Huang 1994; Monserud *et al.* 1990). Though total age is still used (Marton 1998), breast height age is a frequently used value for calculating site index. In this case, instead of stand height and total age being used as the values for calculating site index, the stand height minus breast height (1.3m) and the breast height age are used (Huang 1994). Because tree growth is highly variable in the early years of tree development, a site index based on breast height age is likely to be a better representation of site quality than the use of total height (Carmean and Lenthall 1989). It may take 3-20 years for a tree to grow to 1.3 m (breast height; (Huang *et al.* 1994) depending on the species of the tree, the edaphic conditions, disease, insect attack, and whether or not the tree grew under suppressing conditions (Carmean and Lenthall 1989). The reason height is evaluated rather than other measurements, such as diameter at breast height, is that it is considered to reflect the effects of the environment but is assumed to be relatively unaffected by stand density (Spurr 1952). With species such as lodgepole pine, however, there can be repressed growth in stands that have over 50,000 stems per hectare and the repressed growth could be due to energy being devoted to respiration rather than height growth (Goudie 1980)

1.4.2. Selection of Trees

There are specific criteria that must be met when selecting trees for use in a site index model. Trees that are the largest and healthiest trees on a plot are generally the most desirable for measurement. These will be the trees that have grown without constraints for the entire life of the forest. Thus, these trees would reflect the optimum climax potential for the site. They are trees without disease, without broken tops, and not forked (Husch *et al.* 1982; Monserud 1984).

It is also important that only dominant and co-dominant trees are selected, as opposed to super-dominant, intermediate, or overtopped trees (Forest Productivity Council 2001). The dominant and co-dominant trees are the trees that make up the canopy of the forest. Dominant trees extend above the average level of the canopy and their crowns receive full light from the top and partly from the sides (Smith 1986). Co-dominant crowns form the average height of the canopy and receive full light from the top but have restricted

light from the sides (Smith 1986). This is in contrast to intermediate, overtopped, and super-dominant trees. The crowns of intermediate trees extend into the canopy but receive only limited light from above and no light from the sides, and overtopped trees, or suppressed trees, are below the canopy and receive no direct sunlight. Super-dominant trees or veterans are trees that far exceed the height of the canopy (Smith 1986).

In some regions top height is used to select trees from which to evaluate site index. This involves selecting the largest diameter 100 trees per hectare, which meet the criteria of not being diseased, damaged, or suppressed (Forest Productivity Council 2001).

The selection of site trees assumes that the trees selected have been minimally affected or experienced no effect of being suppressed. With this assumption it is then possible to assume that the selected trees are an accurate reflection of the quality of the location and its ability to supply moisture, nutrients, and light to the growing stand. Species like aspen are potentially a good site species since they are pioneer, shade-intolerant species and are unlikely to grow suppressed under the canopy, as would species such as balsam fir (Burns and Honkala 1990).

1.4.3. Measurements

Factors that need to be measured for site index are height and age. To get these values the trees can be measured using a destructive or non-destructive method. Destructive sampling for stem analysis is the most thorough and reliable method for reconstructing the growth of a tree, and is necessary to get a reliable measure of attained height at reference age. Stem analysis measures the biological growth of the trees whereas following method does not. The alternative to complete stem analysis is non-destructive sampling which would entail taking an increment core using an increment borer. The core would generally be taken at breast height and should reach the pith (Spurr 1952). The age at breast height can then be determined and paired with total height. Since the tree is only measured at one age, no measure of height growth is available for the reference age.

1.4.4. Site Index Curves

In this study polymorphic site curves that were developed in Saskatchewan were used to calculate site index. This was done because; at the time of the study only anamorphic site curves were available for the province of Manitoba.

Both anamorphic and polymorphic curves are developed from multiple data points collected for the study region. Anamorphic, or "proportional", site curves are developed using multiple data points of height and age which can be from trees which were measured by increment core age and height (Davis and Johnson 1987). These data points can then be entered into a model and the average curve for all the trees determined. This curve is then used as the guide curve, and by using ratios predictions can be made for height of trees with site index at the lower and upper end of the data (Davis and Johnson 1987). Anamorphic curves assume that the growth of the trees has the same pattern on the poor sites as well as the productive sites. With anamorphic curves the data is not developed with true growth data that you would get from stem analysis. An alternative strategy is to develop polymorphic curves, which are non-linear models of the tree data that produce different shaped curves for taller or shorter site indices as seen in Figure 1-1 (Davis and Johnson 1987). It can be seen in this figure that the pattern of the growth curve for the site index five metres (SI 5) is different from the site index twenty five metres (SI 25), in with an anamorphic model these two site indices would have the same pattern of growth curves. The polymorphic model is built using data from complete stem analysis of trees from a wide range of site qualities in the study region. Polymorphic models are preferable to anamorphic models since the growth pattern of trees on poor sites will differ from trees on the more productive sites (Davis and Johnson 1987).

These curves are developed by using information, tree height and age, which reflect past growth. Though this information is used to help predict future growth, one should use caution as changes in climate and site characteristics may lead to tree growth that is different from what was found in the past (Kimmins 1990).

1.4.5. Problems with site index

Some difficulties that need to be considered when using site index include accuracy of ring count, regionalism of site curves, and problems associated with mixedwood and uneven aged stands. Some attempts have been made to account for these sources of error.

Some error associated with measuring accurate height-age relationships is from the trees themselves. Rings can be missing from the chronological record, thin growth rings can be difficult to see, and false rings can add to the ring count, thus giving an inaccurate age for the tree (DesRochers and Gagnon 1997; Husch *et al*. 1982). For species such as black spruce it has been shown that the root collar will grow into the ground and that 15 or more years of growth may not be recognized from a ground level measurement (DesRochers and Gagnon 1997). The error associated with the tree ring count cannot necessarily be accounted for and the ages that are counted must be assumed correct.

Site index curves developed for one region will often not work for another. Aspen (*Populus tremuloides*) in British Columbia have been found to require different site index curves than do those in Alberta (Chen *et al*. 1998a). It is reasonable to suspect that this difference is primarily due to regional climate differences. When models developed for Ontario and Alberta were used in British Columbia, it was found that they were biased compared to those developed specifically for the region. The maximum bias was with the Ontario models, which had a bias of 1.8 m shorter at 10 years breast height age compared to Alberta models with a bias of 1.1 m shorter at the same age (Chen *et al*. 1998b).

Generally, site index curves that are established for a region are generated from even-aged, uniform stands. Though there has been some evidence presented that the growth pattern of dominants and co-dominants are similar in uneven-aged stands and even-aged stands of Douglas fir (Monserud 1984). Trying to establish site index in mixedwood, however, does not give as accurate results and site index is not a very powerful tool in this case (Hostin and Titus 1996; Huang and Titus 1993). Other methods of predicting

site productivity in mixedwoods have been attempted. One method for establishing site index in a mixedwood can be to develop a comparative model of site index. In this case, one site index (*e.g., Picea* sp.) is estimated indirectly by the use of the other species (e.g. *Pinus* sp.) growing on that site as shown in the linear model (Wang 1998):

$$SI(sppA) = b_0 + b_1 SI(sppB) \qquad [1\text{-}1]$$

Where,

sppA = site index for species A

sppB = site index for species B

b_0 and b_1 = coefficients to be determined

Site Productivity Index (SPI) has been proposed as alternative to SI as a method for evaluating sites in mixed wood stands. Site productivity index uses height and diameter at breast height as a measure of site quality as opposed to height and age, which is used in site index (Huang and Titus 1993). It has been observed that SPI does not work when used in a pure species, even-aged stands (Wang 1998).

1.5. Soil-site relationships

When forest stands are sampled with plots located on a variety of soil conditions that represent a region, the soils can then be used in environmental predictions. This prediction can be applied to timber productivity, which is useful in forest planning.

The climate and hydrology of a site or region can explain a lot of the variation in site index. Variables such as elevation, latitude, and longitude can be used to model the effects caused by regional climate differences (Klinka *et al.* 1996) and variables such as slope, topographical position, soil moisture regime, depth to gleying, and depth to ground water can be used to represent soil moisture and drainage conditions (Wang 1995; Wang and Klinka 1996). Temperature will decrease with elevation gain and this can affect the length of the growing season and the amount of microbial activity that occurs in the soil. Elevation is included in models where the sites can have large variations in relief (Corns and Pluth 1984; Klinka *et al.* 1996; Monserud *et al.* 1990). A soil-site study in France gave site indices (at 80 years) of 21 m at the crest and 31 m at lower slope positions (Curt

1999). In the sub-alpine forests Klinka modeled engelmann spruce site index with combined elevation and latitude with an R^2 of 0.48. Both were negatively correlated to site index (Klinka *et al.* 1996). The slope position and angle will affect the soil moisture due to drainage, as the drainage will be greater at the top of a steep slope or on the slope compared to a gentler incline or level ground . A steeper slope will be better drained, and tree height has been found to increase with increasing slope up to a limit (Corns and Pluth 1984). Site index for spruce in the interior of British Columbia was modeled using soil moisture regimes and gave an R^2 of 0.57 (Klinka *et al.* 1994). Though it is common for soil moisture-related values to be good predictors of site index (Béland and Bergeron 1996; Corns and Pluth 1984; Monserud *et al.* 1990), there has been evidence that they are not always effective predictors of site index (Bates *et al.* 1992).

Parent material has also been used as a criterion for modeling productivity. Its success in modeling could be due to both the soil texture, which will influence the soil moisture and nutrient-holding abilities of the soil, and to chemical differences in parent material types (Bates *et al.* 1992; Béland and Bergeron 1996; Carmean and Lenthall 1989; Curt 1999). Stratifying by parent material has been found to improve predictive abilities of other edaphic properties (Carmean and Li 1998). Texture of the A and B horizons can also be used as predictors by themselves, giving R^2 values up to 0.85 for the texture of the A horizon predicting site index of *Gmelina arborea* (Henri 2001). Similarly to moisture, there is evidence that parent material is not always found to be an effective variable for predicting tree height growth (Bates *et al.* 1992).

Soil chemical values that commonly enhance these site studies are carbon, total nitrogen, and mineralizable nitrogen; these variables can also be used to generate soil nutrient regimes (Chen *et al.* 1998a; Wang 1995). In one study, the ability of field-determined soil nutrient regimes to predict tree height growth was compared to both quantitatively determined soil nutrient regimes and soil nutrient continuous data. The R^2 values for subalpine fir and engelmann spruce for the nutrient regime estimates were 0.41 and 0.52, and for the clustered nutrient data were 0.41 and 0.47 (Chen *et al.* 1998a). The best results were from nutrient data that were not grouped at all but instead were added into

the model as best subsets (subalpine fir $R^2 = 0.47$ and engelmann spruce $R^2 = 0.65$; (Chen *et al.* 1998a). Similar results were found in another study with nutrient values in site index modeling, though the model was improved when soil data (soil moisture, depth to ground water, and rooting depth) as well as plant data were added to the model (Wang 1995; Wang 1997). In contrast, Monserud *et al.* (1990) found that soil chemical variables did not improve models and suggested that this was due to the large spatial variability inherent in soil chemical characteristics. There are promising results that soil nutrient regimes are useful in soil-site modeling (Chen *et al.* 1998a; Wang 1995). As quantitative soil nutrient regimes are correlated to field identifiable properties, these regimes will become identifiable with less need of expensive nutrient testing. The result of these studies is that site index predictions were improved by the use of field identifiable soil nutrient regimes along with other field identifiable traits. The ability of the models to explain the variation in site index is, however, limited by the range of the data that was collected and the number of data points that were used. A small sample size that is not well distributed to account for most of the environmental variation may have limited prediction power even if reported R^2 values are high.

1.6. Study Area

This study was conducted in the areas on and around the Duck Mountain and Porcupine Hills of Western Manitoba; there were 111 sampling sites (Figure 1-2). Duck Mountain is located northwest of Riding Mountain National Park; the Porcupine Hills are northwest of the Duck Mountain. The study area is bounded by latitudes 52° 50' and 51° 15', and longitudes 101° 40' and 100°30'. Within the study area, elevation varies by approximately 500 m.

The region is on a sedimentary basin and the underlying geology is primarily bentonitic shale, carbonaceous shale, calcareous shale, and limestone (Manitoba Mineral Resources Division 1979). On the northeast side of the Duck Mountain and the Porcupine hills there is a dramatic rise in elevation with about 425 metres rise over a 1400 meter distance giving an average slope of 30 percent. The western sides of the two hill groups gently grade off into the plains on the Saskatchewan side of the border. The topography on the

plateaus tends to be rolling to hummocky whereas the surrounding land tends to be primarily undulating to level (Agriculture Canada 1989). The surficial deposits in the area include morainal, lacustrine, glaciolacustrine, fluvial, and glaciofluvial materials. The Mountains commonly have morainal materials, sometimes with lacustrine veneers. The land surrounding the mountains is mostly glaciolacustrine and morainal material (Agriculture Canada 1989; Zoladeski *et al*. 1998). The glacial drift on the Duck Mountains has been found to be over 300 metres thick and is composed mostly of carbonate-rich moraines (Klassen 1979).

Soils in the forests of the region are most commonly Grey Luvisols, though some Eutric Brunisols and Gleysols may occur as well. Black Chernozems are dominant in the grasslands (Agriculture Canada 1989). The major ecoregions that are present in the study area include the boreal mixed wood, the boreal transition, and the midboreal lowlands. These are all a part of the boreal plains ecozone (Knapik *et al*. 1988). Stand species composition includes common western boreal species: aspen poplar (*Populus tremuloides Michx.*), balsam poplar (*Populus balsamifera L.*), white birch (*Betula papyifera Marsh.*), white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill) BSP.), balsam fir (*Abies balsamea* (L.) Mill.), and jack pine (*Pinus banksiana* Lamb.).

1.7. Methods and materials

1.7.1. Field analyses

Sampling was initiated in 1997 by Louisiana Pacific Canada Ltd. in the summer of 1997 and the author joined the project in January 1999. In the summers of 1997, 1998, and 1999, 333 permanent sample plots (PSPs) were established in the Duck Mountain and Porcupine Hills study area. One-third of the PSPs were selected for detailed soil descriptions and samples were taken of both the mineral soil and the organic forest floor (LFH). Mineral samples were taken from two depths: the top 0-25 cm (surface mineral) and the C-horizon of the soil (subsurface mineral; 70+ cm). As the surface mineral sample included both the A and B horizons, care was taken to sample the entire depth uniformly. Bulk density samples were taken for the forest floor and for the mineral samples. Two bulk density samples were taken from the surface mineral layer to account

for changes between the A and B horizons. The forest floor was sampled using a metal ring so that a known area was sampled at each plot. Field descriptions for the soil and site included slope position, soil drainage class, and moisture regime. All of the descriptions were based on the Forest Ecosystem Classification Guide (Zoladeski *et al.* 1995) and Ecological Monitoring Permanent Sample Plot Field Procedures manual (Louisiana-Pacific Canada Ltd. 2000). At each PSP the dominant and co-dominant trees were selected for measurement of height and age.

Field descriptions for the soil and physiography included slope position, slope angle, aspect, landform type, parent material, humus forms, soil horizons, horizon depth, depth of gleying, depth of mottling, depth of carbonates, depth of rooting, soil drainage class, and moisture regime. All of the descriptions were based on the Forest Ecosystem Classification Guide (Zoladeski *et al.* 1995), The Canadian System of Soil Classification (Soil Classification Working Group 1998), and Ecological Monitoring Permanent Sample Plot Field Procedures manual (Louisiana-Pacific Canada Ltd. 2000).

At each PSP the dominant and co-dominant trees were selected for measurement of height and age. Height was measured with a clino-meter. Cores were taken using an increment bore, and retained for ring counts to determine the age of the tree at breast height (1.3m).

Ten vegetation types (v-types) were included in this study. The range of v-types included hardwood, hardwood-dominated mixedwood, and conifer-dominated mixed wood. Though there are very few pure conifer stands within the study region, conifer stand types may be measured at a later date. These were not measured for this study. The following is a list of the v-types sampled in the study and their abbreviations (Zoladeski *et al.* 1995):

V-1: Balsam poplar hardwood and mixedwood

V-4: White birch hardwood and mixedwood

V-5: Aspen hardwood

V-6: Trembling aspen- Balsam fir/ mountain maple/ herb-rich

V-8: Trembling aspen- mixedwood/ tall shrub

V-9: Trembling aspen- mixedwood/ low shrub

V-13: White spruce mixedwood

V-15: Jack pine mixedwood/ shrub-rich

V-16: Jack pine mixedwood/ feather moss

V-17: Black spruce mixedwood/ shrub- and herb-rich

1.7.2. Laboratory analyses

Soils were sampled during the spring through to fall, and the nutrients that the soils were analyzed for are relatively unaffected by the change of season (Tisdale *et al.*). The collected soil samples were air-dried the same day they were sampled and then were transported to the University of Alberta for laboratory analyses. All samples were analyzed for pH in water. The pH of the mineral soils was measured in a 1:2 soil (weight) to solution (volume) slurry (10g soil: 20ml of water) and the organic with a 1:5 soil to solution ratio (5g soil: 25ml of water; (Hendershot *et al.* 1993b). As well, total nitrogen (N_T), and organic carbon ($C_{org.}$) were measured in all samples by dry combustion with a Carlo-Erba (<0.5g of soil; (Tiessen and Moir 1993). Dry combustion measures total carbon; as the mineral soil was often rich in carbonates the soil was pre-treated with HCl before analysis.

Depending on whether the sample was forest floor, surface mineral, or subsurface mineral, different analyses were conducted. Both the forest floor and surface mineral soil were analyzed for cation exchange capacity (CEC) and exchangeable cations (calcium, magnesium, potassium, sodium) by ammonium acetate extraction at pH 7.0 (10g of soil for mineral soil or 2g for organic). The concentrations of ions in the extracts for CEC were measured using an Technicon II autoanalyzer (Hendershot *et al.* 1993a). The concentrations of exchangeable cations extracts were measured using a Perkin Elmer 503, atomic absorption spectrophotometer. The CEC was not determined on the subsurface samples due to the high carbonate contents of these soils. Total phosphorous (P_T) was determined on the forest floor sample by acid digestion; the concentration of phosphorus in the digestion product was then analyzed on an autoanalyzer (0.2g of soil; (Karam

1993). Extractable phosphorous was determined on 10-g subsamples by the modified Kelowna method for both the surface mineral and subsurface mineral samples (Ashworth and Mrazek 1995). Again, total phosphorus in these extracts was measured with the autoanalyzer.

Physical analyses included particle size analysis, bulk density, and corrected bulk density. Particle size analysis was done using the hydrometer method (Sheldrick and Wang 1993). The amount of soil used depended on the soil texture; for silty and clayey soils 30-40g was used and for sandy soils up to 100g was used. Mineral samples were collected in 100 cm^3 bulk density cores then brought into the lab and oven-dried to determine the bulk density of each sample. To determine the corrected bulk density, all coarse fragments (>2mm) were removed from the sample and weighed. An average particle density of 2.65 g cm^{-3} (Hillel 1980) was estimated for these fragments and their volume was calculated. The mass of rock fragments was then subtracted from the total mass and the fragment volume was subtracted from the original volume of the cores. The new values were then used to calculate the corrected bulk density. The corrected bulk density was used to calculate the concentration of nutrients at each site. The rocks from the forest floor samples were removed and the mass of the air-dry forest floor was recorded. The mass and the known area were used to determine forest floor dry mass by area (FFDM) and were also used to calculate nutrient mass on an area basis.

1.8. Remaining chapters

In chapter two, soil nutrient regimes were established and their chemical properties described. In chapter three, soil nutrient regimes of one vegetation type were investigated to find field identifiable traits that could be used to distinguish the regimes in the field. The soil nutrient regimes were also tested for their usefulness when predicting site index; this was done in conjunction with and contrast to other soil properties. The synthesis, chapter 4, will discuss some of the implications of the earlier chapters, as well as speculating on ways to improve or refine future research of this type.

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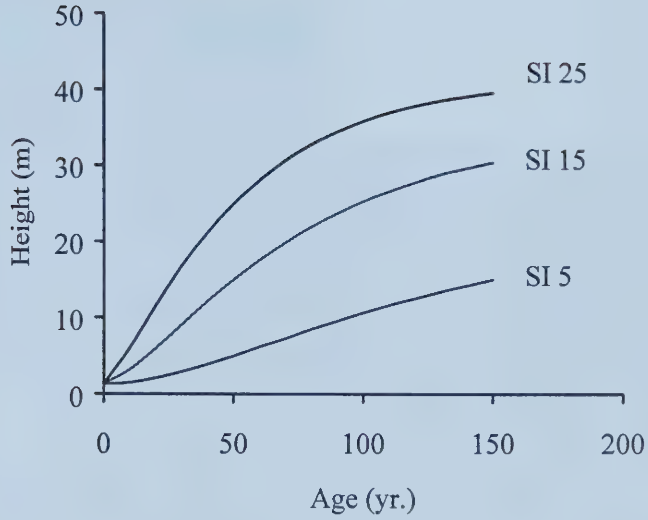

Figure 1-1. Polymorphic growth curves (SI = site index (m), base age for the model = 50; species = Lodgepole pine (*Pinus contorta* var. latifolia Engelm.); developed from data in Huang *et al* 1994).

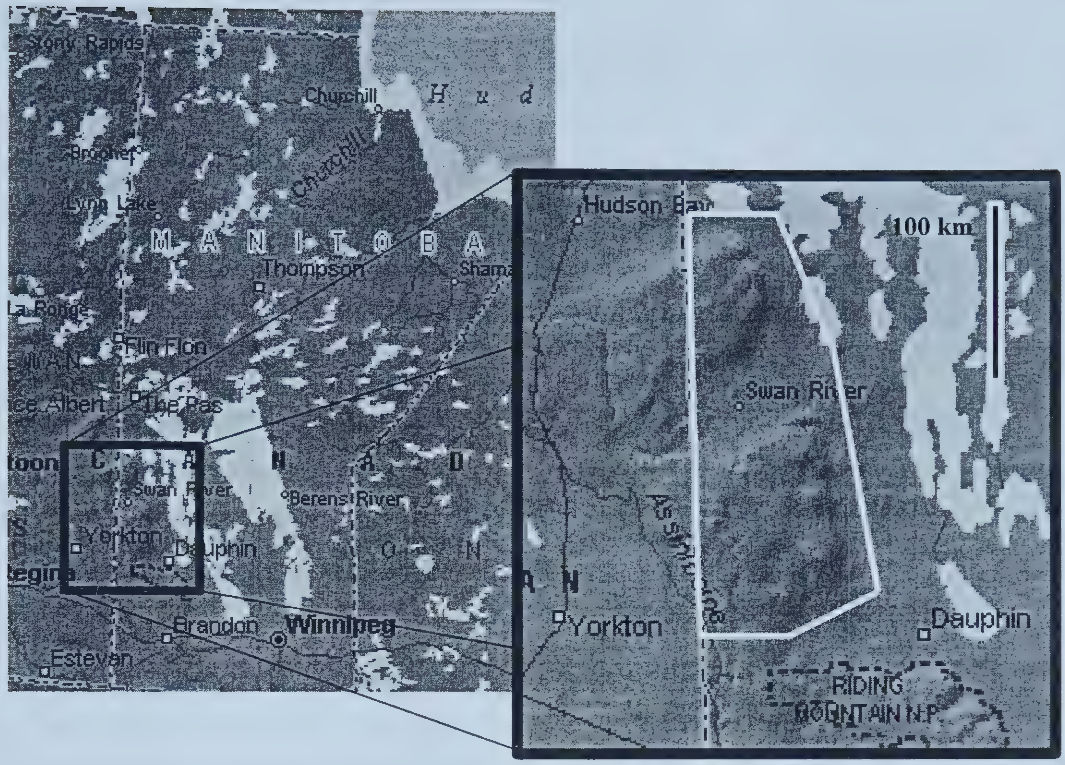

Figure 1-2. Regional map of study area (white boundary in blowout outlines the study area).

CHAPTER 2. SOIL NUTRIENT REGIME CLASSIFICATION

2.1. Introduction

Ecological classification has become a commonly used tool in Canada to assist in land use decisions for resource management. Soils have been a key component of forest classification since it was first applied in Canada (Hills 1952). The use of soils in forest classification continues in all the regions that have developed classification systems (Corns 1992; MacKinnon *et al*. 1992; Sims and Uhlig 1992). Hills (1952) recognized ecoclimate, soil moisture, and soil nutrient regime as the three main physiographic reference features in forest classification. Of these, the soil nutrient regimes are the most expensive to quantify due to the cost of laboratory analysis; they are also perhaps the most difficult to establish, as there are multiple geologic, biologic, and climatic interactions that generate the measurable nutrient status of a soil. Soil nutrient regimes (SNR) are "a class of presumed soil nutrient gradient, and thus represents a similar level of soil nutrient availability for a population of soils" (Klinka *et al*. 1994). Establishing the classes that define this gradient in the Duck Mountain and Porcupine Hills region of Manitoba is the focus of this chapter.

In Manitoba there are established field procedures for assessing soil moisture classes and soil drainage (Zoladeski *et al*. 1995). Moisture conditions and the texture class of the parent material are used to assess soil types, or "S" types. Soil nutrient regime, in the Manitoba field guide, can only be field-assessed based on the plant community. Within any given plant community there can be a variety of site conditions. Differences can result from type of parent material, soil moisture, soil aeration, and topographic characteristics that create climatic differences. These sites are also likely to have variation in soil nutrient status. Soil nutrient regimes are useful to assist in the assessment of site. It would also be desirable to eventually link the SNRs with field-measurable traits so that a field assessment can be made of the nutrient status.

There are now well-established SNRs in the province of British Columbia that have been developed with field measurable soil properties. These soil properties have been used to

develop dichotomous keys, which can in turn be used to classify a new area into the soil nutrient regimes (Klinka *et al*. 1994; Pojar *et al*. 1987). Field-identified SNRs based on these keys have been consistent when tested with soil chemical data (Chen *et al*. 1998; Wang 1997). The dichotomous keys have since been modified for use in other regions such as Alberta (Beckingham *et al*. 1996). A key of this sort is beyond the scope of this study, but an evaluation of the environmental relationships in this region could help the initial establishment of such a tool. In this study soil nutrients measured in the laboratory were used to classify the sites into soil nutrient classes. This will be the initial development of quantitative SNRs for the study region.

The purpose for producing the soil nutrient regimes is to replace the need for expensive soil nutrient analysis with field identifiable regimes. The end product will be soil nutrient regimes that represent available nutrient gradients and can be estimated in the field, by field measurable traits.

The objective of this chapter was to develop preliminary soil nutrient classes in the Duck Mountain, Porcupine Hills region of Manitoba.

2.2. Methods and materials

2.2.1. Field and laboratory methods

These are outlined in detail in chapter one. The data that were used for the statistical analyses in this section included the soil nutrient data from the forest floor and the surface mineral soil. Field collected data that were used for comparisons included vegetation type, soil moisture regime, soil drainage class, and slope position.

2.2.2. Statistical analyses

A flow chart of data analyses used can be seen in Figure 2-1. Data were initially analyzed using principle components analysis (PCA) and regression analysis to help find which variables were meaningful for predicting site index and grouping the soil nutrients. The soil nutrients were grouped using selected variables in K-means cluster analysis. The number of cluster groups was selected by choosing the cluster output that had the

lowest number of groups that maximized the sum of squares between cluster groups and minimized the sum of squares within groups. Backward elimination procedure in discriminant analysis was used to determine which variables best defined the established groups. The groups were then checked for misclassification using discriminant analysis. Once the groups were established, the nutrient measurement means were compared among groups by analysis of variance followed by Bonferroni multiple pairwise comparison tests ($p<0.05$; Moore and McCabe 1989; Tables 2-8, 2-9, and 2-10). Soil nutrient regimes were assigned labels: very poor (VP), poor (P), moderate (M), rich (R), and very rich (VR). These were assigned based on the group averages of the soil properties, in particular C:N of the mineral soil and the FFDM. Discriminant functions were then produced for the five classes (appendix A). The discriminant functions were produced so that plots that are established in the future with the same data gathered can be classified into the soil nutrient regimes. Statistical analyses were performed using SYSTAT 10 (SPSS 2000).

2.3. Results and discussion

2.3.1. Rational for selection of certain laboratory analyses

The modified Kelowna method (Ashworth and Mrazek 1995) was selected for extracting phosphorus because the pH for the soils ranged from 5 to 9. Extractable phosphorus is a pH-dependent measurement and the modified Kelowna method is a robust method for soils that range from slightly acid to slightly alkaline. This method was also found to be work well to predict plant yield when tested in agricultural studies (McKenzie *et al.* 1995).

The region is also very high in soil carbonates. This creates a problem with particle size analyses as the carbonates can cause flocculation of fine soil particles making the smaller particles combine and be measured as larger particles. The result is a poorly-represented clay, and sometimes silt, fraction. The carbonate content of these soils was so high, commonly over 10% and sometimes up to 40%, that they were not removed before analysis; their presence was so great that they contribute to the particle distribution of the mineral soil (Klassen 1979; Robertson 1961).

2.3.2. *Variable selection*

Because there were few variables that could predict site index some of the soil chemical variables were not required to establish the soil nutrient regime (SNR) groups. Soil nutrients were also investigated using PCA and correlation matrices to find variables that were highly correlated. Highly correlated variables were not included in the analysis at the same time. Because total nitrogen (N_T) was highly correlated with organic carbon (C_{org}) they were not included in cluster analyses or discriminant analyses at the same time (Table 2-1). As well, no subsurface mineral samples were used because they are only distantly associated with the biological cycling of elements that dominate near the soil surface (Ekelund *et al.* 2001; Fyles and McGill 1987). Initial trials of regression analyses revealed that the sub-surface variables had little relationship to site index. For economic reasons it was also desirable to keep the number of variables used to establish the groups low so that new plots could easily and affordably be added to the classification.

Selected properties of the surface soil and LFH were used to establish the SNR groups. These were selected both by examining the data and by referring to variables that were useful in published studies. Mineralizable nitrogen (N_{min}) is an assay that measures the amount of nitrogen that the microbes in a soil can potentially make available to plants under optimum conditions and has been found to correlate with plant uptake of mineral nitrogen (Fyles *et al.* 1990). It has been found to be an important indicator for soil nutrient quality (Chen *et al.* 1998; Kabzems and Klinka 1987; Powers 1980; Reganold and Palmer 1995; Wang 1997). In one study N_T in the mineral soil was found to be well correlated to N_{min} (Klinka *et al.* 1994); because of this N_T may give SNR groupings similar to using N_{min}. In another study N_T was successfully used as a variable to establish SNR groups (Courtin *et al.* 1988). Soil nutrient regimes were established in England using other mineral nitrogen variables (NH_4^+ and NO_3^-; Wilson *et al.* 2001). As we did not measure N_{min} in this study, the clustering was attempted using the N_T of the mineral soil. When the mineral soil chemistry was analyzed by principal components analysis N_T had one of the highest loadings in the first factor; when the model was rotated this effect was consistent. Nitrogen was also found to correlate with C_{org} and calcium, and calcium

with magnesium. In Figure 2-2 the first three factors can be seen plotted with the original PCA analysis. These three factors account for about 72% of the variability. Along with N_T our SNR groups were derived from carbon to nitrogen ratio (C:N) of the mineral soil and forest floor dry mass (FFDM). Due to its success with modeling site index in this and other studies the C:N ratio of the mineral soil was included to establish the nutrient regimes (Chen *et al*. 1998; Klinka *et al*. 1994). The use of FFDM as a property to establish the SNR groups is, to my knowledge, novel; I have found no prior reports of its use in the literature. It was included because of its success in predicting site index in the region. Also, the forest floor thickness and density does not necessarily vary between species in one climatic region but can vary between site locations making it a potential indicator of biological site quality (Alban 1982).

In this study, if the classes do represent a combination of increasing nutrient availability and biological activity then the hypothesized trend would be that mineralizable nitrogen will steadily increase from the VP to the VR groups. Since mineralizable nitrogen was not analyzed, forest floor dry mass and C:N ratio of the surface mineral soil were used as biologic productivity and available nutrient indicators for the soil. Both of these variables have been found to have little variation caused by overstory species type in the boreal forest, with the exception of black spruce (*Picea mariana*; Van Cleve *et al*. 1983). As the study area included mixedwood forest this was important so that all plots could be represented on a scale independent of stand species type. Carbon to nitrogen ratio is a valuable tool for assessing the amount of nitrogen that can be made available to plants. In soils with wide ratios microorganisms can immobilize nitrogen making it unavailable (Brady and Weil 1996). The forest floor gives a representation of plant biomass productivity as it contains input of organic matter from all of the above ground plants. Not only is the mass of the forest floor relatively independent of species composition but it should also be relatively independent of age when comparing mature stands. In particular the cycling of nutrients under aspen has been found to be quite rapid. Reported average turnover rates of the aspen forest floor in Alaska being generally ten to fifteen years (Van Cleve and Noonan 1975). A mature forest will be much older than this so the forest floor inputs and outputs should be in a steady state, and age should not be a major

factor in affecting the mass. It should be emphasized that the FFDM includes the mass of mineral soil that is mixed into it. Although using mineralizable nitrogen can be a proven and acceptable way of determining soil nutrient status, using forest floor dry mass, along with C:N of the surface mineral soil, may be a useful, quicker, and less expensive alternative for the study region.

K-means cluster analysis was used to group the data into soil nutrient regimes (SNR) using FFDM, C:N ratio, and N_T. K-means analysis is sensitive to outliers, so four of the investigated plots were removed from the total data set (Figure 2-3). Using discriminant analysis, stepwise selection was performed to find which variables were needed to define the groups (Figure 2-1). The results indicated that C:N and FFDM were the only two variables that were necessary. The number of plots that were correctly classified decreased only slightly from the model with N_T (Table 2-2) compared to the model without N_T (Table 2-3). The misclassified plots were then re-classified into their predicted groups until no further misclassifications occurred. The resultant classification gives two distinct groups for the R and VR classes that are separate from the other three groups when the first two principle components are plotted, and the other three groups are in a tight cluster.. The VP, P, and M groups had minimal separation between each other (Figure 2-4).

2.3.3. Ranking the groups

The five groups were assigned rankings, before the discriminant analysis was run, based on the variables used for the cluster. High FFDM and narrow C:N ratio define the richer classes and the reverse defines the poorer classes. This was not a linear trend however and some interpretation had to be made when determining a letter rank. Most groups could be ranked based primarily by visual inspection of C:N and FFDM (Figures 2-5 and 2-6). Classes VP and P required some interpretation in assigning their order as one had higher FFDM and the other a narrower C:N ratio. They were arranged based on C:N ratio because the C:N ratio of the mineral soil is likely more indicative of the long-term quality of the site than FFDM. This indication is because the humin in the mineral soil of Grey Luvisols has a mean residence time of about 335 years (can be longer depending on

soil characteristics; Campbell *et al.* 1967) and the forest floor is generally the product of the current forest stand. Unlike what was found in the British Columbia studies of soil nutrient regimes (Chen *et al.* 1998; Klinka *et al.* 1994; Wang 1997), the N_T did not give an upward trend from poor to rich. It showed very little difference between groups (Figure 2-7). The richest (VR) sites did, however, have wider C:N ratios. They were ranked as nutrient rich due to the higher concentration of nutrients and the larger FFDM values for the sites.

2.3.4. Properties of the groups

Of the ten vegetation types (V-types) sampled, five were represented by more than five plots, and only one had more than thirteen. Two of the V-types had only one plot sampled. The aspen hardwood V-type (V-5) had a total of 50 plots sampled that were included in establishing the nutrient groups (not including two of the four plots removed by outlier analysis). Of the possible 50 combinations of these V-types and SNR, 29 occurred in our data (Table 2-4). Soil moisture regimes (SMR) and SNR combinations were well represented by 28 plots and soil drainage class combinations with SNR totaled 24 plots (Table 2-5 and 2-6). Crest, upper, mid and level slope positions were well represented (Table 2-7). Only 5 plots of the 107 sampled were located at lower slope positions and no plots were located at toe slopes or in depressions. Though there could have been a better representation of the lower slope positions, the range of possible plant communities, soil moisture, soil drainage, elevation, latitude, and longitude does represent most of the ecological conditions and geography of the forested parts of the region.

Significant differences among SNR groups were found in most of the nutrient data for the forest floor and in the forest floor dry mass (Bonferroni, $p<0.05$; Table 2-8). There were no significant differences among groups for forest floor C:N ratio, CEC, and pH. For the most part, the nutrients in the forest floor followed the same pattern for significant differences between groups, as did the FFDM since the nutrient concentrations were generated using FFDM. The most notable differences in the FFDM values were between

the VP, P, M groups and the R to VR groups. In these cases the high forest floor mass of the latter two groups set them apart as rich, high plant productivity sites.

There were significant differences in the mineral soil, among the groups for N_T, C_{org}, C:N, sodium, and CEC (Table 2-9). The VR nutrient class was significantly higher than the other classes in some of the measured nutrient variables, including N_T, C_{org}, sodium, and CEC. This, along with the high FFDM values, distinguished it as the richest nutrient group. The VP nutrient class also had high N_T and C_{org} and had the highest C:N ratio as well. It is likely that these very poor sites did not have the optimum edaphic conditions for the microorganisms to break down and cycle the inputs of organic material to the soil. The poorer three groups (VP, P, M,) can be distinguished primarily by their C:N ratio which from VP to M gives a clear trend of P having a narrower ratio than VP, M narrower than P, and with R being narrower than only VP (Figure 2-6).

When the soil nutrients from both the forest floor and the surface mineral soil were combined, the VR group had higher concentrations of N_T, C_{org}, and magnesium than the VP, P, and M classes (Table 2-10). Magnesium was the one nutrient that had no notable differences between groups in the mineral soil; when magnesium (mineral soil) was combined with magnesium (forest floor), a trend appears, however significant differences were detected only between VR and all of VP, P, and M (Figure 2-8). As the mineral soil magnesium content (by mass) is one order of magnitude greater than the mass of magnesium in the forest floor, this trend would be unlikely to exist if there was not a trend developing in the mineral soil. As two different forms of phosphorous were measured in the samples, depending on whether the sample was mineral or organic, phosphorus could not be combined in such a manner.

The status of these soil nutrient groups is not directly comparable to the groups that have been established in British Columbia. In British Columbia the forested soils are often sandy with high coarse fragments and low pH compared to the silty/clayey, low coarse fragment, neutral to high pH soils of Western-Manitoba (Knapik *et al.* 1988; Wang and Klinka 1996). The sandy, high coarse fragment soils will have a lower CEC, and the

nutrients will be more susceptible to leaching, and the low pH will put chemical constraints on the plant available nutrients (Brady and Weil 1996). In this case the nutrients will be more limited in supply. In the neutral silty and clayey soils nutrient limits may not be the determinant of plant growth to the same degree as the former due to neutral pH and high CECs. Because of this, the correlations of soil nutrient status to plant growth may be obscured. In boreal systems phosphorous and calcium are found to be important nutrients to species such as aspen and white spruce (Alban 1982; Chapin *et al.* 1986; Flanagan and Van Cleve 1983; Gordon 1981; Strong and La Roi 1985). It would have been expected that some relationship between phosphorus and the soil nutrient regimes would be found in this study. The reason that such a relationship was not found may be because there were minimal nutrient limitations in the soil of the study region. The glacially deposited sediments may have been rich in available nutrients for plant uptake. Also, the nutrients that were limiting in these soils may not have been measured for this study. It may also be worth considering that these groups represent both nutrient regimes and bio-productivity regimes at the same time, and that these two factors cannot be viewed as mutually exclusive.

2.3.5. Further work in the study region

As mentioned earlier, potentially mineralizable nitrogen could be an asset in establishing these nutrient classes. Another factor, which could improve the quantitative classification of nutrients, would be smaller depth increments. Chemical and physical properties can change dramatically between soil horizons and the 0-25cm depth sample may have been comprised of more than one horizon (Alban 1982; Fyles and McGill 1987; Reganold and Palmer 1995). The depth sample may be masking some of the complex pedogenic differences between sites by mixing soil horizons; to correct this, one could break the samples into smaller increments. Although the plots were well distributed across the study region, it would be useful to sample a larger variety of slope positions, slope angles, slope forms, and aspects to obtain an even more thorough data set. Topography has been found to correlate well with tree productivity (Corns 1983; Corns and Pluth 1984; Curt 1999; Wang 1995)

2.4. Conclusion

Both the dry mass of the forest floor and the carbon to nitrogen ratio were useful tools to differentiate soils into groups for the study region. These groups, or regimes, are a representation of both soil nutrient status and biological productivity. It is important to mention that these soil nutrient groups are subjective. Further investigation is needed to validate the soil nutrient regimes proposed in this thesis.

2.5. References

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Table 2-1. Pearson correlation matrix of surface mineral nutrients (numbers are pearson correlation, "R", values).

	N[1]	C[2]	P[3]	Ca[4]	Mg[5]	K[6]	Na[7]
N[1]	1						
C[2]	0.942	1					
P[3]	0.385	0.305	1				
Ca[4]	0.507	0.500	0.450	1			
Mg[5]	0.506	0.395	0.382	0.422	1		
K[6]	0.450	0.435	0.306	0.167	0.284	1	
Na[7]	0.350	0.258	0.019	0.160	0.295	-0.106	1

1= total nitrogen, 2= organic carbon, 3= extractable phosphorus (modified Kelowna), 4= calcium, 5= magnesium, 6= potassium, 7= sodium.

Table 2-2. Classification matrix from discriminant analysis (DA) of SNR categories using total nitrogen, carbon to nitrogen ratio, and forest floor dry mass (cases, DA classification, in rows, categories, the original classification, classified into columns).

			SNR			
SNR	**VP[1]**	**P[2]**	**M[3]**	**R[4]**	**VR[5]**	**% correct**
VP[1]	22	0	0	0	0	100
P[2]	0	41	1	0	0	98
M[3]	1	1	28	1	0	90
R[4]	0	0	0	7	0	100
VR[5]	0	0	0	0	5	100
Total	23	41	29	8	5	96

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

Table 2-3. Classification matrix from discriminant analysis of SNR categories using carbon to nitrogen ratio and forest floor dry mass (cases, DA classification, in rows, categories, the original classification, classified into columns).

			SNR			
SNR	**VP[1]**	**P[2]**	**M[3]**	**R[4]**	**VR[5]**	**% correct**
VP[1]	20	2	0	0	0	91
P[2]	2	39	1	0	0	93
M[3]	1	0	30	0	0	97
R[4]	0	0	0	7	0	100
VR[5]	0	0	0	0	5	100
Total	23	41	31	7	5	94

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

Table 2-4. Number of plots in each combination of soil nutrient regime and vegetation type.

	Vegetation-type										
SNR	**1**	**4**	**5**	**6**	**8**	**9**	**13**	**15**	**16**	**17**	**Total**
VP[1]	3	0	13	0	2	2	2	0	0	0	22
P[2]	1	1	16	1	7	2	5	4	3	2	42
M[3]	2	0	15	0	3	5	4	0	0	2	31
R[4]	1	0	3	0	1	1	0	1	0	0	7
VR[5]	1	0	3	0	0	0	1	0	0	0	5
Total	8	1	50	1	13	10	12	5	3	4	107

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich. Vegetation type numbers defined in text.

Table 2-5. Number of plots in each combination of soil nutrient regime and soil moisture regime.

	Soil moisture regimes							
SNR	**MD_M**[6]	**MF_M**[7]	**F_M**[8]	**VF_M**[9]	**MM_M**[10]	**M_M**[11]	**VM_M**[12]	**Total**
VP[1]	1	4	8	5	2	2	0	22
P[2]	3	5	14	11	5	3	1	42
M[3]	1	2	11	10	5	2	0	31
R[4]	0	0	1	1	2	1	2	7
VR[5]	0	1	0	2	1	1	0	5
Total	5	12	34	29	15	9	3	107

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich, 6= moderately dry, 7= moderately fresh, 8= fresh, 9= very fresh, 10= moderately moist, 11= moist, 12= very moist.

Table 2-6. Number of plots in each combination of soil nutrient regime and drainage class.

SNR	VR_D[6]	R_D[7]	W_D[8]	Drainage classes MW_D[9]	I_D[10]	P_D[11]	VP_D[12]	Total
VP[1]	2	4	10	3	3	0	0	22
P[2]	3	3	19	5	7	1	0	42
M[3]	2	0	19	7	3	0	0	31
R[4]	0	0	2	1	3	1	0	7
VR[5]	1	0	1	1	1	0	1	5
Total	8	7	51	17	17	2	1	107

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich, 6= very rapid, 7= rapid, 8= well, 9= moderately well, 10= imperfect, 11= poor, 12= very poor.

Table 2-7. Number of plots in each combination of soil nutrient regime and slope position.

SNR	Crest	Upper	Slope position Mid	Lower	Level	Total
VP[1]	5	3	5	1	8	22
P[2]	9	11	13	2	6	42
M[3]	1	13	9	1	7	31
R[4]	0	1	2	0	4	7
VR[5]	0	1	3	0	1	5
Total	15	29	32	3	26	107

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

Table 2-8. Forest floor: chemical values for each soil nutrient regime. Values are means with standard deviations in brackets. Within rows values followed by the same letter are not significantly different (Bonferoni $p<0.05$).

			SNR		
	VP[1]	P[2]	M[3]	R[4]	VR[5]
N_{tot}	1.84a	1.04b	1.95a	3.21c	5.77d
Mg ha^{-1}	(0.66)	(0.42)	(0.55)	(1.11)	(1.83)
C_{org}	36.48a	21.97b	38.85a	65.61c	107.56d
Mg ha^{-1}	(11.07)	(8.06)	(8.02)	(22.46)	(30.56)
C:N	20.3a	21.6a	20.4a	20.6a	18.8a
	(2.7)	(3)	(3)	(2.1)	(2.2)
P_{tot}	102.9a	62.2b	132.4ac	160.7c	303.5d
kg ha^{-1}	(42.3)	(25.3)	(60.2)	(46.2)	(90.1)
Ca	210.2a	103.7b	206.5a	330.7c	583.3d
kg ha^{-1}	(96.3)	(46.9)	(73.6)	(164.1)	(232.9)
Mg	214.5a	121.5b	220.9a	397.6c	656.2d
kg ha^{-1}	(97.7)	(63.3)	(77.8)	(180.2)	(131.8)
K	96.4a	65.8b	103.5a	113.9a	206.8c
kg ha^{-1}	(24.3)	(25.4)	(32)	(47.3)	(56)
Na	3.5ab	1.7a	3.3ab	6.1ab	17.3b
kg ha^{-1}	(2.9)	(1.8)	(4.5)	(3.5)	(10.1)
CEC	76a	80.6a	73.8a	69.4a	85.6a
cmol (+) kg^{-1}	(25)	(26)	(14.1)	(29.3)	(24.3)
pH	6.3a	6.1a	6.4a	6.3a	6.5a
	(0.7)	(0.5)	(0.4)	(0.6)	(1.2)
FFDM	125.17a	70.59b	123.75a	225.88c	334.44d
Mg ha^{-1}	(25.08)	(22.15)	(19.26)	(32.85)	(34.85)

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

Table 2-9. Surface mineral soil: chemical values for each soil nutrient regime. Values are means with standard deviations in brackets. Within rows values followed by the same letter are not significantly different (Bonferoni p<0.05).

	SNR				
	VP[1]	**P**[2]	**M**[3]	**R**[4]	**VR**[5]
$\mathbf{N_{tot}}$	3.65a	2.70b	3.04ab	2.39ab	5.08a
Mg ha^{-1}	(1.35)	(0.89)	(0.83)	(0.82)	(1.85)
$\mathbf{C_{org}}$	44.36a	27.66b	28.56b	23.24b	56.33a
Mg ha^{-1}	(15.90)	(8.78)	(8.43)	(8.71)	(18.04)
C:N	12.3a	10.3b	9.3c	9.7bcd	11.2abd
	(1.3)	(1.2)	(0.9)	(1.2)	(1)
$\mathbf{PO_4^-}$	72.2a	78.3a	86.5a	72.8a	94.9a
kg ha^{-1}	(26.7)	(18.9)	(26.6)	(24.8)	(50.4)
Ca	10.48a	7.91a	9.33a	7.50a	15.75a
Mg ha^{-1}	(5.82)	(5.62)	(5.01)	(3.44)	(5.88)
Mg	1.41a	1.47a	1.72a	1.59a	2.43a
Mg ha^{-1}	(0.54)	(0.69)	(0.75)	(1.00)	(1.05)
K	785.4a	490.2a	589.4a	422.9a	458.7a
kg ha^{-1}	(777.7)	(286)	(369.9)	(379.9)	(240.2)
Na	27.5a	34.2a	44.9a	30.3a	140.6b
kg ha^{-1}	(20.8)	(21.8)	(28.6)	(21.2)	(159.6)
pH	7.2a	7.1a	7a	7.2a	7.9a
	(0.6)	(0.8)	(0.8)	(0.8)	(0.5)
CEC	23.5a	18.5a	22.8a	19a	41.1b
cmol(+) kg^{-1}	(13.1)	(9.1)	(10.6)	(10.1)	(12.9)

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

Table 2-10. Combined surface mineral and forest floor: chemical values for each soil nutrient regime. Values are means with standard deviations in brackets. Within rows values followed by the same letter are not significantly different (Bonferoni p<0.05).

	SNR				
	VP[1]	**P**[2]	**M**[3]	**R**[4]	**VR**[5]
N_{tot}	5.12a	3.90b	5.05a	5.60a	10.86c
Mg ha^{-1}	(1.87)	(1.16)	(0.98)	(1.57)	(2.83)
C_{org}	75.90a	51.64b	67.97a	88.86a	163.90c
Mg ha^{-1}	(24.70)	(14.29)	(11.82)	(26.33)	(42.88)
Mg	1.49a	1.72a	1.90a	1.99ab	3.09b
Mg ha^{-1}	(0.57)	(0.73)	(0.75)	(1.12)	(1.09)
C:N	15.14a	13.41b	13.57b	15.95a	15.08ab
	(1.77)	(1.40)	(1.30)	(2.28)	(0.86)

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

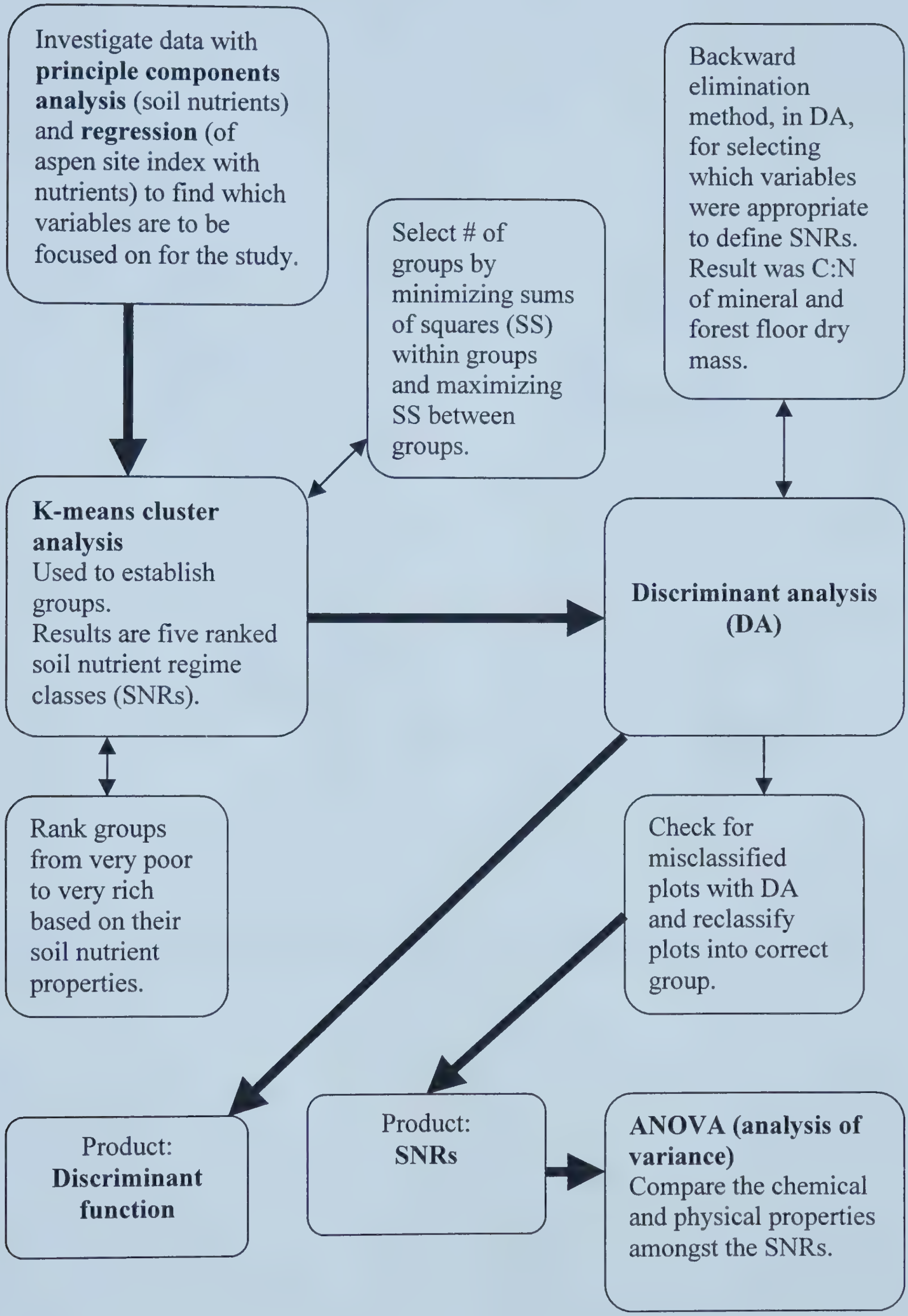

Figure 2-1. Flow chart of statistics used in chapter 2.

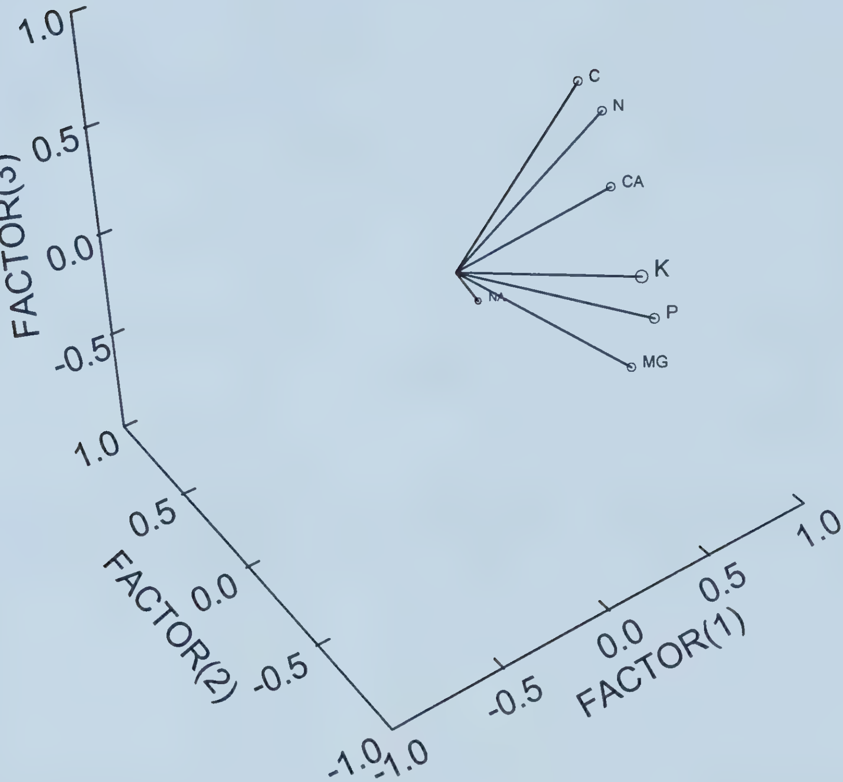

Figure 2-2. Principal components analysis factor loadings plot for surface mineral nutrients.

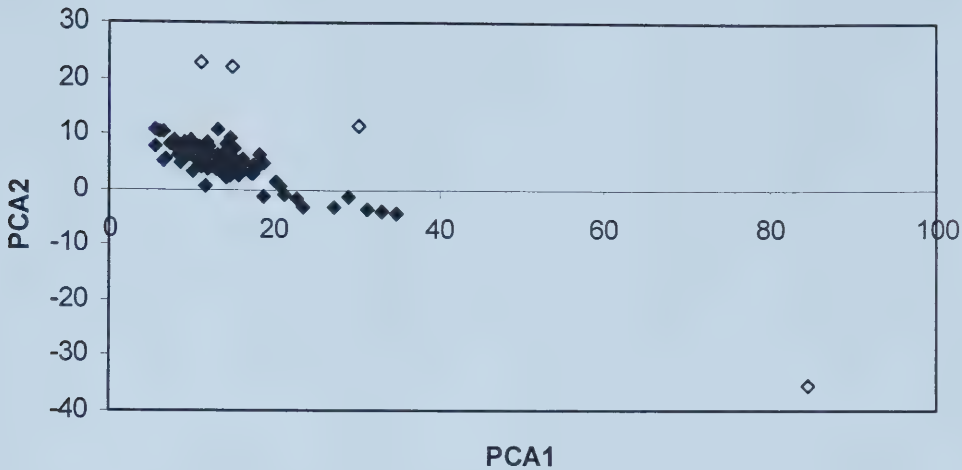

Figure 2-3. Factors one and two of principal components analysis using total nitrogen, carbon to nitrogen ratio of the surface mineral soil, and forest floor dry mass. Points that were identified as outliers are highlighted by hollow dots.

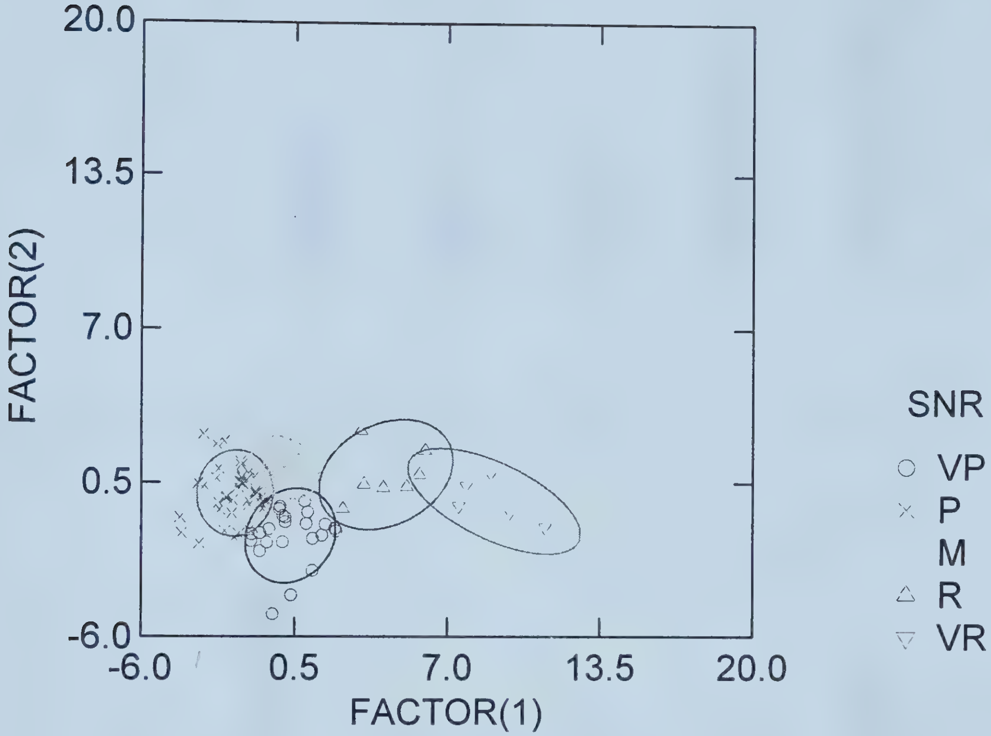

Figure 2-4. Canonical scores plot. The ellipses define the general boundaries of the groups. Factor one and two were generated with data from forest floor dry mass and carbon to nitrogen ratio of the surface mineral soil.

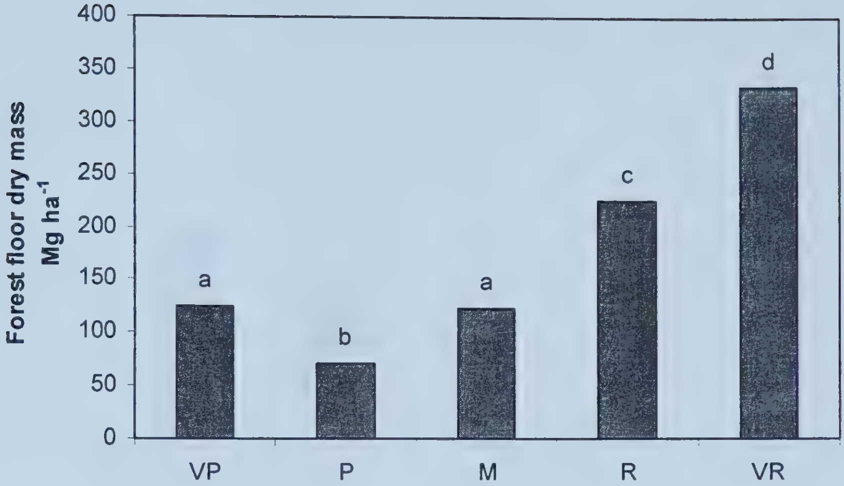

Figure 2-5. Forest floor dry mass of the soil nutrient groups (bars topped by the same letter are not significantly different, Bonferoni $p<0.05$).

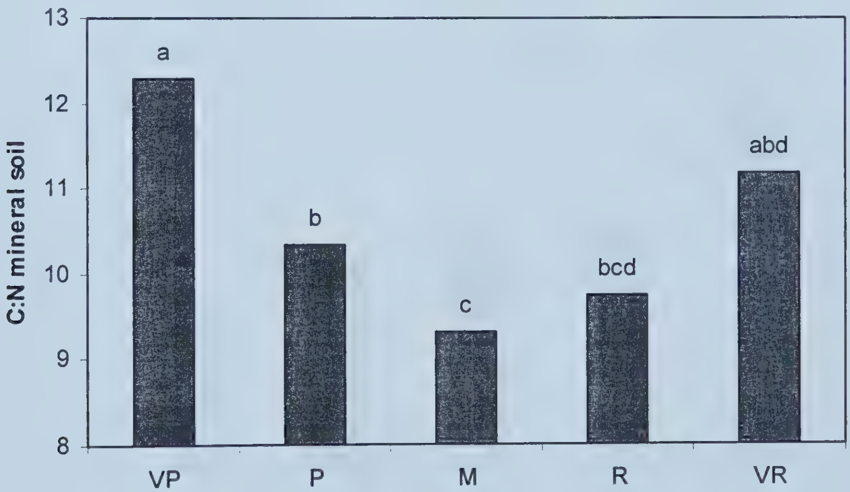

Figure 2-6. Carbon to nitrogen ratios of the soil nutrient groups for surface mineral soils (bars topped by the same letter are not significantly different, Bonferoni $p<0.05$).

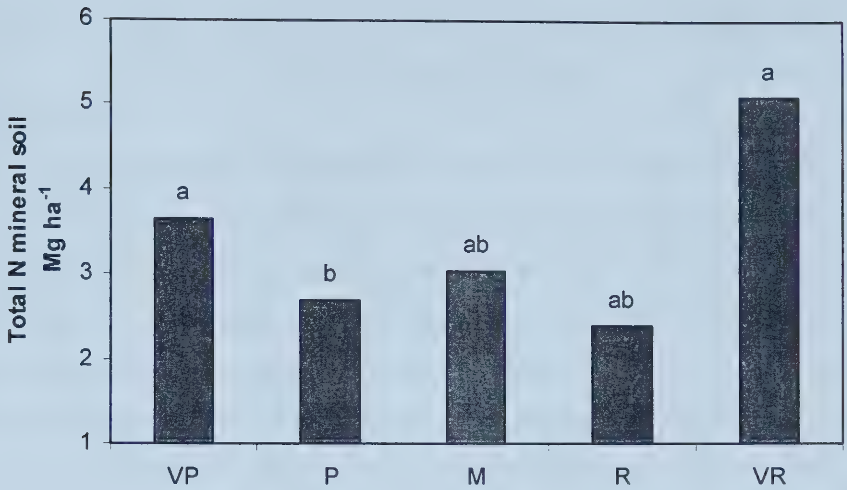

Figure 2-7. Total nitrogen content of the soil nutrient groups for surface mineral soils (bars topped by the same letter are not significantly different, Bonferoni $p<0.05$).

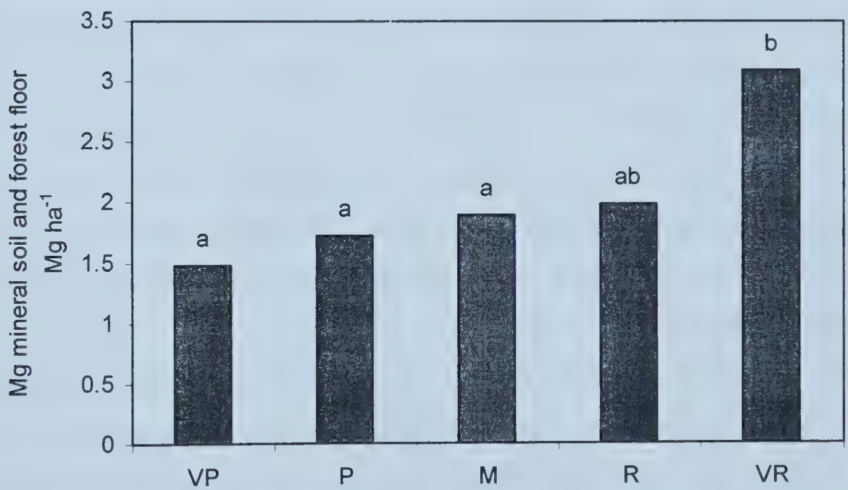

Figure 2-8. Combined mineral soil and forest floor magnesium content of the soil nutrient groups (bars topped by the same letter are not significantly different, Bonferoni $p<0.05$).

CHAPTER 3. SOIL-SITE RELATIONSHIPS IN ASPEN AND MIXEDWOOD STANDS

3.1. Introduction

Site index is a common method for estimating the productivity of forests in North America. It is defined as the average height of the dominant trees or dominant and co-dominant trees at a reference age, usually 50 years (Barnes *et al*. 1998; Huang 1994). One attractive property of site index is that it is relatively unaffected by the stand density, compared to volume predictions which are affected by density (Spurr 1952). Differences in productivity between locations depend, in part, upon soil property differences. These differences can be seen in the growth of the trees; trees have been described as the "phytometers" of the soil (Monserud *et al*. 1990). Thus, it is possible to predict tree growth potential using soil properties and characteristics as indicators.

The ability to predict the productivity of a location is useful for forecasting the re-growth of a stand under forest management. One of the main questions may be the volume of timber that a location can produce after a harvest. Site index may be an indirect measure of timber volume productivity for a given location (Carmean 1996; Davis and Johnson 1987). Site index is developed in pure, even aged forest stands with only one tree species and canopy trees of the same relative age, such that the trees are growing unsuppressed by a forest canopy and the only limitations to their height are the properties of the soil and climate (Barnes *et al*. 1998). This can cause difficulties in extrapolating site index to predict the productivity of a mixedwood stand. Site index has also been found to be less successful in predicting the growth of a young forest, and models that are to be used have to be corrected for the underestimated growth of these forests (Magnussen and Penner 1996). Because there are some difficulties with the prediction of re-growth and half of the study area for this project is mixedwood forest, alternatives to using site index to predict forest productivity may be desirable.

Soil properties have been found to be good indirect estimators of site index and have been used to model tree growth in many studies across North America. Values such as parent material type, depth of horizons, colour of the soil, depth of roots, coarse fragment

content, soil moisture regime, depth of water table or other water-related variables have been used to model forest productivity (Béland and Bergeron 1993; Corns 1978; Monserud *et al.* 1990). In British Columbia, researchers found excellent correlations in both coastal and interior forests by modeling site index with soil nutrients. Using combined soil nutrient and soil moisture regimes, Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) productivity was modeled on the west coast, yielding an R^2 of 0.84 (Klinka and Carter 1990). In other regions such as the northwest United States and central Europe, researchers found that soil nutrients as model variables predicted site poorly (Gömöryová and Gömöry 1995; Monserud *et al.* 1990).

Soil physical, chemical, and morphological properties are not the only measurable site predictors. Vegetation can be correlated to soil nutrient properties and this has been found to be excellent for predicting site; when coupled with soil, climate, and geologic variables vegetation can often account for much of the variation in site (Corns and Pluth 1984; Wang 1995). Corns and Pluth (1984) found that vegetation data improved soil-site models significantly in west-central Alberta. Using variables such as deadfall cover and percent cover of selected understory plants with soil and topographic variables, site index prediction of lodgepole pine (*Pinus contorta* Dougl. Var *latifolia* Engelm.) was improved from an R^2 of 0.49 (soil variables only) to an R^2 of 0.71 (soil and vegetation variables) and site index prediction of white spruce (*Picea glauca* (Moench) Voss) improved from R^2 of 0.58 (soil variables only) to an R^2 of 0.91 (soil and vegetation variables) (Corns and Pluth 1984). Though vegetation is a desirable indicator of site index, the study presented here was primarily concerned with predicting site productivity through the use of soil and topographic variables and the establishment of soil nutrient classes.

The objectives of this chapter were: 1) To determine field-identifiable traits of the soil nutrient regimes; 2) To evaluate the soil nutrient regimes that were established for this study in modeling forest productivity; 3) To model aspen (*Populus tremuloides* Michx.) site index in the Duck Mountain, Porcupine Hills region of Manitoba using edaphic properties.

3.2. Methods and materials

3.2.1. Field and laboratory methods

The field and laboratory methods are outlined in detail in chapter one. The data that were used for the statistical analysis in this section included the laboratory generated soil nutrient and physical data of the forest floor and the surface mineral soil. Field-collected information included soil and topographic variables. The only vegetation data that were used were aspen site index and vegetation types.

3.2.2. Site index calculation

Site index was established for each plot using the Saskatchewan polymorphic site curves (Cieszewski and Bella Unpublished). These curves were used because there were no polymorphic curves available for Manitoba at the time of the study. The curves are generated using a modified half saturation function (Cieszewski, C.J. and Bella, I.E. 1989). A half saturation function calculates the time it takes a stand to reach half of its maximum height growth. The curves are described by equation (1):

$$H = \left[\frac{\left(h_x + \left[b/50^a \right] + \sqrt{\left(h_x - \left[b/50^a \right] \right)^2 + 4bh_x/x^a} \right)}{2 + \left(\dfrac{4b/t^a}{h_x - \left[b/50^a \right] + \sqrt{\left(h_x - \left[b/50^a \right] \right) + 4bh_x/x^a}} \right)} \right] + 1.3 \qquad (1)$$

Where:

H = computed tree height (m)

t = prediction age (years)

50 = reference age

h_x = measured height of tree (m) - 1.3 m

x = measured age of tree at breast height (years; 1.3m)

a and b = predicted coefficients for tree species used

For aspen:

a= 1.185685

b= 1360.651

This model predicts height of a stand at a new age using the field-collected age and height. To generate site index the prediction age used is fifty years. Because site index for aspen was being predicted the coefficients "*a*" and "*b*" that were generated in the original model for aspen were used. All trees that were measured for age and height were run in this model individually to produce height predictions for age fifty years. For each plot the individual values that were generated were then averaged to give one value, which was the site index (example calculation in Appendix B).

3.2.3. Statistical Analyses

K-means cluster analysis was used to group the nutrient data into soil nutrient regimes (SNR; chapter 2). Five SNRs were defined: very poor (VP), poor (P), moderate (M), rich (R), and very rich (VR). For the established SNRs the means of the field measureable traits were compared among groups by analysis of variance followed by Bonferroni pairwise comparison tests (alpha<0.05). This was done only for the V-5 plant community because the sample size in the others was considered inadequate for making these tests. The groups were then regressed against site index of trembling aspen. Models were fitted using both categorical and analytical data, and avoiding the use of both analytical nutrient data and the new categorical SNR data in the same model. Categorical variables were converted into dummy variables, which involves changing qualitative variables into several related binary variables (Kachigan 1991). An example of this would be the five soil nutrient regimes used in the study. The regimes are labelled from very poor to very rich. There are five numbers to represent each plot four "zeros" and one "one". If the plot in question were very poor then 1,0,0,0,0 would represent it, but if it were poor then 0,1,0,0,0 would represent it. Statistics were performed using SYSTAT 10 (SPSS 2000).

3.3. Results and discussion

3.3.1. Aspen-hardwood, soil nutrient regime properties

Field-identifiable soil properties and site index were compared within the V-5 plots between SNR groups. This was done with only one vegetation type to reduce the effect

of species composition on the measurable soil properties. The V-5 plots were favoured over the other vegetation types as they are a non-mixedwood stand type and a relatively large number of plots were sampled. Of the field-identifiable properties measured (eg.: slope angle, humus form, rooting depth, depth and type of horizons, etc), only three showed significant differences: site index, root depth, and humus form (Bonferroni $p<0.05$; Tables 3-1 and 3-2). Most of the field data did not show trends that differentiate the SNR groups from each other.

The only significant difference in aspen site index was between SNR VP and M. A plot of the group means shows that there was a general upward trend from VP to M with a plateau from M to VR (Figure 3-1).

The field-measured soil variable with the best trend by SNR and significant differences among SNRs was root depth (Figure 3-2). With increasing soil nutrient class from poor to rich the average depth of the roots were shallower. Root depth was defined as the lowest depth (from the mineral soil surface) where the roots were abundant (Agriculture Canada 1982). Used in the field, this definition was subjective, as the root size and density were not quantitatively estimated to decide on this depth; it was intended for the field personnel to rule out the occasional deeper root that can be found at the bottom of a soil pit. Aspen growing on sandy soils have been found to have a denser root pattern deeper into the soil profile when compared to aspen growing on fine-textured soils. It is suggested that this may be due to the succession of a deeper rooting climax species growing under the canopy (Strong and La Roi 1983). This deeper rooting could also be due to a need for soil nutrient and water resources that the sandy or less nutrient rich soils are not able to supply, and the result is roots mining further down the soil profile. Root density is highly correlated to phosphate concentration in the soil, even more than to water holding capacity (Strong and La Roi 1985). Based on this it would be reasonable to hypothesize that the changes in root depth with SNR are due in part to nutrient availability.

The presence of modor humus form was found to be a significant indicator of very rich sites. Though this was the only statistically significant finding for this variable type some patterns can be seen in the data. In general, the modor humus form was more common in richer sites, fibrimor occurred in all sites, and humimors were found in the poorer nutrient sites (Table 3-2). In the dichotomous keys developed for predicting SNR in British Columbia and Alberta, modors and mulls are used to help identify richer soils and mors are more common on poorer soils (Pojar *et al*. 1987). Similar correlations of forest floor type to site quality have been found in the United Kingdom as well. In this region, different forms of mull define the medium to rich regimes, modors defined the poor to medium sites, and mor humus forms defined the very poor sites (Wilson *et al*. 2001).

The results of this study suggest that the depth and type of the A horizon, root depth, slope position, and humus form merit further investigation in future studies in the Duck Mountain study area. In conjunction with other field indicators, these observations may be useful for determining soil nutrient regimes and modeling forest productivity. This would reduce the need for further nutrient analyses and the associated costs.

3.3.2. Soil-Site Relationships

Site indices were regressed using all possible plots, aspen-hardwood plots only, and aspen hardwood stratified by parent material. Some plots did not have trees over twenty years old and other plots were removed after they were investigated and determined to be outliers, so that not all of the 111 sample plots sampled were used. Outliers were investigated and removed prior to cluster analysis for establishing the nutrient groups due to large forest floor dry mass values and very wide carbon to nitrogen ratios (Figure 2-3). Plots that had site trees of less than 20 years were not included in the regression analysis as there is the possibility of a large over or under prediction of site index with site trees of young age (Davis and Johnson 1987). Also equations 2 and 4 (Table 3-3) used 79 plots as apposed to the possible 93 used in equations 3, 5, and 6 (Table 3-3) since there were some elevation data points missing. All reported models were significant ($p<0.05$; Table 3-3 Equations 2-6, Table 3-4 Equations 7-11, and Table 3-5 Equations 12-15) with no significant pattern in the residual plots (Appendix C; Graybill and Iyer 1994). The

categorical data were transformed into dummy variables and the coefficients in the models that were associated with these variables represent aspen site index averages. The dummy variables were v-types, soil nutrient regimes, soil drainage classes, and soil moisture regimes.

The models developed for the entire data set showed significant relationships with vegetation type, P_{FF} (kg ha^{-1}), surface soil Ca (kg ha^{-1}), elevation, soil nutrient regimes, and soil moisture regimes. The soil nutrient regimes were found to successfully model site index only when vegetation variables were in the model (equation 5 and 6, Table 3-3). The best models for this data set included vegetation type as variables (eqations 3, 5, and 6 Table 3-3) and yielded R^2 values of 0.51-0.55.

Changes in plant communities and biomass production have been attributed to changes in elevation according to some of the ecological literature (Chen *et al.* 1998; Corns and Pluth 1984; Curt 1999; Monserud *et al.* 1990). Because of this, the decrease in site index with increasing elevation was expected and can be seen when plotted (Figure 3-3). The elevation change, however, cannot explain all the variation in site index. As seen in equation 2, there is a very weak relationship between site index and elevation (R^2=0.12; Equation 2, Table 3-3). Using only edaphic properties along with elevation explains more of the variation (R^2=0.41; Equation 4 Table 3-3). Elevation also helps to explain the increased presence of conifer-dominated stands on the elevated plateaus compared to the aspen-dominated lowlands because plant community will also change with elevation (Corns 1983).

Micro-site variations are also likely to affect the growth of aspen due to the preference of the species for specific environmental conditions. Aspen is more likely to grow on parent materials such as morainal deposits rather than glacial fluvial deposits that often have Jack pine (*Pinus banksiana* Lamb.; Bridge and Johnson 1999). An aspen growing on these types of soils can be missing required nutrients or moisture for growth. Also, species such as Black spruce (*Picea mariana* [Mill.] BSP.) have been found to grow on soils with higher moisture contents and will generate a thick, insulated, and cooler forest

floor. Those conditions are not conducive to good aspen growth (Van Cleve *et al.* 1983). Such micro-site factors, along with the regional climate changes caused by elevation are likely the cause of the lower site index of aspen growing in the conifer mixed wood stands as seen in equations 3, 5, and 6 (Table 3-3).

In most of the models soil moisture or drainage contributes to predicting site index (Equations 4 and 6 Table 3-3, Equations 8-11 Table 3-4, and Equations 12-15 Table 3-5). These variables are both water descriptors, as they are identified based on soil texture and signs of water restriction (Zoladeski *et al.* 1995). Variables that qualitatively or quantitatively describe soil moisture, drainage, and aeration are commonly found to be dominant factors in the prediction of forest productivity (Béland and Bergeron 1993; Carmean 1996; Wang 1995; Wang and Klinka 1996). Because of this strong relationship, less influential variations due to the soil nutrients can be difficult to detect.

Nutrient variables that were found to be successful for modeling aspen site index included P_{FF}, C:N, and Ca (Equations 3 and 4 Table 3-3, Equations 7 and 9 Table 3-4, Equations 12 and 14 Table 3-5). The C:N ratio of mineral soil and forest floor have been found in British Columbia to model tree growth with an R^2 of up to 0.41 with no other variables included in the model (Klinka *et al.* 1994). Phosphorus and calcium have also been found to be important nutrients to species such as aspen and white spruce (Flanagan and Van Cleve 1983). One study in Denmark found forest floor carbon content to be negatively correlated to phosphorus and calcium concentration in mineral soil (Vesterdal and Raulund-Rasmussen 1998). As our models predicted increasing nutrient regime quality with increasing forest floor mass, the earlier reported negative trend with phosphorus contradicts our findings (Figure 2D). It is possible that the forest floors that are represented in the Danish study have mull forest floors in the richer nutrient sites; this information was not reported. Studies in England found that mull forest floors were found at the medium to rich plots (Wilson *et al.* 2001). Mull humus forms would have less organic matter than modors or mors as they are relatively unmodified litter on top of mineral soil. Modors and mors were the most abundant humus forms in our study region which could explain the discrepancies between our findings and these other studies.

Aspen and white spruce have been found to have high requirements for calcium and phosphorus (Alban *et al.* 1978). Calcium removal from the surface mineral soil is significantly greater under aspen and white spruce (Alban 1982) and a negative relationship with site could be a reflection of good tree growth. Although there is no evidence, one explanation for a negative relationship between site and calcium is that the free calcium is precipitating the phosphorus and the lack of available phosphorus is limiting tree growth. The precipitation to of phosphorus is more likely to be in high pH soils and most of the surface mineral soils in the region are neutral to only slightly basic. It is also very likely that the relationship that was found in the model generated in this study could be mere coincidence.

Using categorical soil nutrient regimes, the site index prediction was improved only slightly compared to the continuous soil nutrient property data models. Equation 3 (Table 3-3) had an R^2 of 0.53 and Equation 9 an R^2 of 0.49, compared to the categorical model equivalents in Equation 5 (Table 3-3) which had an R^2 of 0.55 and equation 10 with an R^2 of 0.54. This is similar to what was found in a west-coast Douglas fir forest where the categorical representations of soil nutrients did improve the modeling of site compared to continuous nutrient data, but only marginally (Klinka and Carter 1990).

Stratifying the V-5 vegetation type by parent material (Equations 12-15 Table 3-5) improved the models of site prediction from the models of all V-5 data (Equations7-11 Table 3-4). One of the more promising models was for lacustrine parent material (20 plots) where site index was regressed with SNR and SMR giving an $R^2$of 0.72, an adjusted R^2 of 0.62, and a standard error of estimate (SEE) of 1.1 m (Equation 13 Table 3-5). This is comparable to work done in Ontario where site index of aspen was predicted on glaciolacustrine deposits (20 plots) using clay content of the C horizon (%) and depth to mottles (cm) giving an adjusted R^2 of 0.65, and a SEE of 1.46 m (Carmean and Li 1998). Other similar results were found in the same study with two other parent material types. The other two parent material types from our study, moraine and glaciofluvial, had only 14 plots each and although the predictions were improved

substantially from the non-parent material stratified models, caution should be used when drawing inferences from these (Equations 14 and15 Table 3-5). The small sample size used in a regression with a large number of independent variables could give an artificially high R^2 value thus produce a model with an inflated ability of the independents to predict the dependant variable, in this case site index. It should be noted that Carmean and Li (1998) found that aspen did not grow to maturity on the poorest sites and that the models they generated are only applicable to the medium to high quality sites where there is good stocking of aspen (Carmean and Li 1998). It is likely that the same applies to our study.

3.4. Conclusion

Site index of aspen can be predicted with use of edaphic variables. The most successful predictions were derived when soil nutrient regimes were used in conjunction with soil moisture or drainage variables. Stratifying the data by parent material and vegetation type allowed the models to be further improved. The aspen sites were likely representative of medium to highly productive soil and the poor sites may have been underrepresented. There is evidence that phosphorus concentrations, calcium concentrations and carbon to nitrogen ratio are chemical parameters that merit further investigation for site prediction. Soil nutrient regimes can be identified based on soil variables such as humus form and root depth, though more work needs to be done to validate these variables as predictors of soil nutrient regime. Of the models developed the most useful are the ones stratified by both vegetation type and parent material. Of these the glaciolacustrine aspen hardwood model predicting site index with soil nutrient regime and soil moisture regime was the most useful (Equation 13 Table 3-5). The models developed for the other parent should be used with caution as the sample size was very small (Equations 14 and 15 Table 3-5). The next most useful models for predicting site index are the aspen hardwood models of which the one with soil nutrient regimes explains the most variability (Equation 10 Table 3-4). Of the all plots data the models with both soil nutrient regime and vegetation type explain the most variability and one isa as good as the other (Equations 5 and 6 Table 3-3). It would be worthwhile, when possible, to use more than one model to help predict site index.

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Table 3-1. Site index, soil properties, and landform characteristics of each soil nutrient regime type, for the V-5 vegetation type only. Values are means with standard deviations in brackets. Within rows, means followed by the same letter are not significantly different (Bonferroni $p<0.05$).

			SNR		
	VP[1]	P[2]	M[3]	R[4]	VR[5]
SI (m)	20.5a (1.7)	21.8ab (2.1)	23.2b (2.1)	23.7ab (2.7)	23.6ab (2.2)
Root depth (cm)	44.4a (14.4)	38.6a (12.6)	39a (11.4)	18b (2.6)	16b (1.7)
LFH depth (cm)	8.8a (6.5)	9a (6.3)	8.6a (6.1)	10a (2.6)	8.8a (4.5)
Depth of A (cm)	10a (6)	8.7a (4.1)	10.1a (5.8)	6a (6)	8.7a (4.7)
Depth of A+B (cm)	53.1a (11.8)	53.4a (11.1)	61.2a (15)	44.3a (12)	41.7a (12.4)
Elevation (m)	493.3a (140.1)	564.4a (120.3)	494.8a (137.1)	385.7a (57.9)	382.5a (180.3)
Slope (%)	3.1a (4.3)	6.1a (7.3)	3.9a (5.4)	1a (1)	2.7a (2.1)

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

Table 3-2. Number of plots in each combination of humus form types and soil nutrient regime. For the V-5 (aspen hardwood) vegetation type only. Within rows, values followed by the same letter are not significantly different (Bonferroni $p<0.05$).

			SNR			
Humus form	VP[1]	P[2]	M[3]	R[4]	VR[5]	Total
Humimor	4a	1a	2a	0a	0a	7
Fibrimor	7a	14a	11a	2a	0a	34
Moder	2a	0a	2a	1a	3b	8
Mull	0a	1a	0a	0a	0a	1
Total	13	16	15	3	3	50

1= very poor, 2= poor, 3= medium, 4= rich, 5= very rich.

Table 3-3. Models for the regression of aspen site index (m/50 years) with selected categorical[1] and continuous[2] data. Models are based on all vegetation types measured in the study.

(2) $SI = 25.3 - 0.01(\text{elevation})$

$R^2 = 0.12$ adjusted $R^2 = 0.11$ $F = 10.2$ SEE = 3.3m n = 79

(3) $SI = 21.4 + 0.01(P_{FF}) - 0.1(Ca) - 3.08(V8) - 2.44(V9) - 4.59(V13) - 6.07(V15) - 5.94(V17)$

$R^2 = 0.53$ adjusted $R^2 = 0.49$ $F = 13.4$ SEE = 2.4 m n = 93

(4) $SI = 14.4 - 0.01(\text{elevation}) + 0.01(P_{FF}) - 0.2(Ca) + 11.2(MF_M) + 9.9(F_M) + 11.0(VF_M) + 11.2(MM_M) + 10.8(M_M) + 10.2(VM_M)$

$R^2 = 0.41$ adjusted $R^2 = 0.34$ $F = 5.38$ SEE = 2.9 m n = 79

(5) $SI = 19.01 + 1.5(M) + 2.6(R) + 2.3(VR) + 2.4\,(V5) - 1.2\,(V8) - 2.3(V13) - 3.7(V15) - 4.7(V17)$

$R^2 = 0.55$ adjusted $R^2 = 0.51$ $F = 12.8$ SEE = 2.4 m n = 93

(6) $SI = 16.4 + 1.5(M) + 3.8(R) + 2.4(VR) + 2.4(MF_M) + 1.2(F_M) + 1.9(VF_M) + 3.8(V5)$

$R^2 = 0.51$ adjusted $R^2 = 0.47$ $F = 12.6$ SEE = 2.4 n = 93

[1]Categorical Data: V5, V8, V9, V13, V15, V17 refers to vegetation community types, MF_M = moderately fresh, F_M = fresh, VF_M = very fresh, MM_M = moderately moist, M_M = moist, VM_M = very moist, M = medium nutrients, R = rich nutrients, VR = very rich nutrients.

[2]Continuous data: P_{FF} = forest floor total Phosphous kg ha^{-1}, Ca = mineral soil Calcium Mg ha^{-1}, elevation = m.

Table 3-4. Models for the regression of aspen site index (m/50 years) with selected categorical[1] and continuous[2] data. These models use only the V5 (aspen hardwood) vegetation type measured in the study.

(7) $SI = 27.3 + 0.11(FFDM) - 0.63(C{:}N)$

$R^2 = 0.16$ adjusted $R^2 = 0.12$ $F = 4.12$ $SEE = 2.1$ m $n = 47$

(8) $SI = 23.0 - 3.07(R_D) - 2.43(MW_D) - 2.64(P_D)$

$R^2 = 0.31$ adjusted $R^2 = 0.26$ $F = 6.44$ $SEE = 1.9$ m $n = 47$

(9) $SI = 26.6 + 0.11(FFDM) - 0.40\,(C{:}N) - 0.10\,(A\ depth) - 2.72\,(R_D) - 2.19\,(MW_D) - 3.26(P_D)$

$R^2 = 0.49$ adjusted $R^2 = 0.41$ $F = 6.34$ $SEE = 1.7$ m $n = 47$

(10) $SI = 22.4 + 0.87(P) + 1.9(M) + 2.95(R) + 3.03\,(VR) - 0.08(A\ depth) - 2.23(R_D) - 2.18(MW_D) - 3.55(P_D)$

$R^2 = 0.54$ adjusted $R^2 = 0.44$ $F = 5.49$ $SEE = 1.7$ m $n = 47$

(11) $SI = 25.1 - 0.12(A\ depth) - 0.03(Root\ depth) - 3.03(R_D) - 2.44(MW_D) - 2.94(P_D)$

$R^2 = 0.41$ adjusted $R^2 = 0.34$ $F = 5.72$ $SEE = 1.8$ $n = 47$

[1]Categorical Data: R_D = rapid drainage, MW_D = moderately well drained, P_D = poorly drained, P = poor nutrients, M = medium nutrients, R = rich nutrients, VR = very rich nutrients.
[2]Continuous data: FFDM = forest floor dry mass kg m^{-2}, C:N = carbon to nitrogen ratio of the mineral soil, Root depth and A depth = cm.

Table 3-5. Models for the regression of aspen site index (m/50 years) with selected categorical[1] and continuous[2] data. These models use only the V5 (aspen hardwood) vegetation type measured in the study and stratified by parent material.

Glaciolacustrine
(12) $SI = 25.6 + 0.01(P_{FF}) - 0.53(C{:}N) - 2.02(F_M) + 0.94(VF_M) + 1.86(M_M)$ $R^2 = 0.64$ adjusted $R^2 = 0.51$ $F = 5.01$ SEE = 1.2 m n = 20
(13) $SI = 22.5 - 2.07(VP) - 1.51(P) - 1.79(F_M) + 0.871(VF_M) + 1.27(M_M)$ $R^2 = 0.72$ adjusted $R^2 = 0.62$ $F = 7.02$ SEE = 1.1 m n = 20
Glaciofluvial
(14) $SI = 21.1 + 0.03(P_{FF}) + 0.18(\text{LFH depth}) - 0.22(\text{A depth}) - 2.10(MF_M) - 4.16(F_M)$ $R^2 = 0.75$ adjusted $R^2 = 0.59$ $F = 4.74$ SEE = 1.4 m n = 14
Moraine
(15) $SI = 23.1 - 4.26(VP) - 2.88(P) - 0.14(\text{LFH depth}) + 0.08(\text{Depth Carbonates}) - 3.87(MM_M) - 3.70(VM_M)$ $R^2 = 0.81$ adjusted $R^2 = 0.65$ $F = 5.07$ SEE = 1.6 m n = 14

[1]Categorical Data: MF_M = moderately fresh, F_M = fresh, VF_M = very fresh, MM_M = moderately moist, M_M = moist, VM_M = very moist, VP = very poor nutrients, P = poor nutrients.
[2]Continuous data: P_{FF} = forest floor total Phosphorus kg ha^{-1}, C:N = carbon to nitrogen ratio of the mineral soil, LFH depth, A depth and Depth of carbonates = cm.

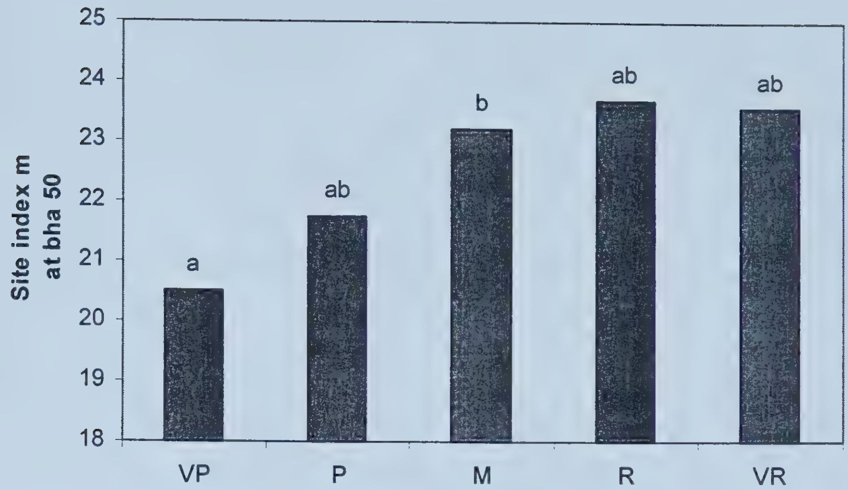

Figure 3-1. Aspen site index averages plot by soil nutrient regime (Bars topped by same letter are not significantly different Bonferroni p<0.05).

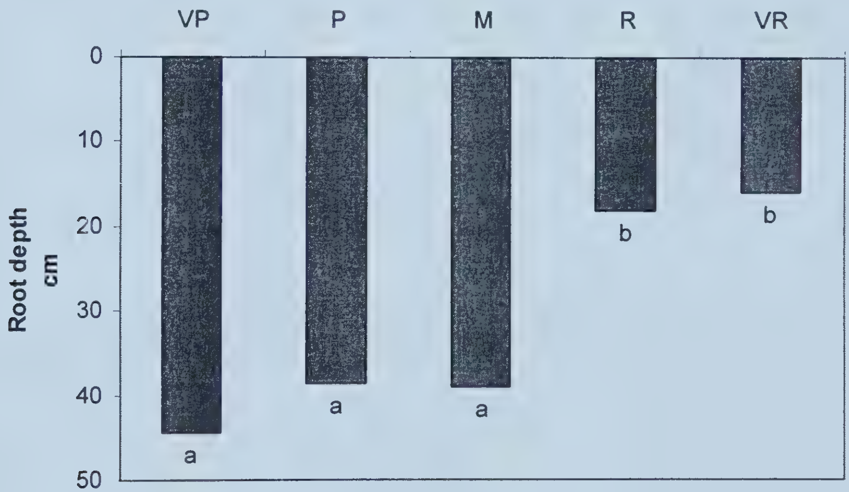

Figure 3-2. Root depth averages plot by soil nutrient regime (Bars topped by same letter are not significantly different Bonferoni p<0.05).

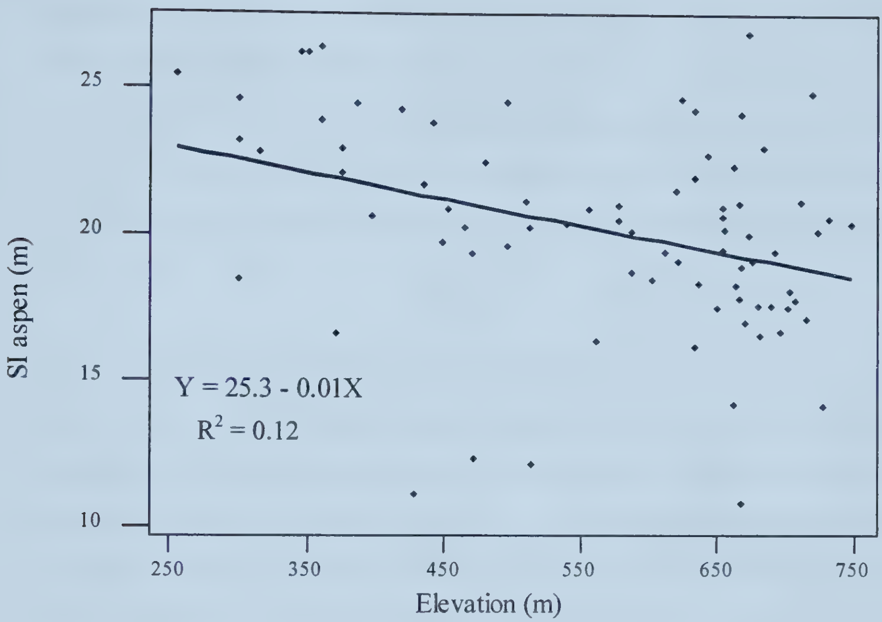

Figure 3-3. The relationship between aspen site index and elevation. Trend line taken from Equation 2 (Table 3-3).

CHAPTER 4. SYNTHESIS

This thesis was about how to measure and describe a forest and then use that information to predict the productivity of the same forest. The soil nutrient regimes that were developed in this thesis are one way of assessing and describing the soils of the study region; they are related to the productivity of the forest. Soil nutrient regimes have not been well developed for the boreal forest to date as they rely heavily on work that has been done in British Columbia. This thesis demonstrates their potential in this region. British Columbia, with its strict forestry code of practice, has been the leader in this type of research and soil nutrient regimes are being used there with great success (Klinka *et al.* 1994).

These nutrient regimes may be costly to establish, because the price of soil analyses is high. However, once the regimes are established and reliable field identifiable traits can be connected to these regimes, the lab analyses may be replaced by quicker field assessments that can be made by foresters. If further research is to be done on developing nutrient regimes in the boreal plains, attention should be paid to the work that is being done in British Columbia as a framework for developing regimes on the boreal plain. as The use of variables such as potentially mineralizable nitrogen would be a good variable for helping to refine soil nutrient regimes (Chen *et al.* 1998; Courtin *et al.* 1988; Klinka *et al.* 1994; Wang 1997). As well, stratifying the data at broad scales, such as by parent material, can improve the ability of soil properties to predict productivity (Carmean and Li 1998).

To classify soils into nutrient regimes the discriminant functions developed for this study can be applied. This requires that only the forest floor dry mass and the C:N ratio of the mineral soil need to be collected. The benefit of having nutrient classes based on these two factors is that future analyses can be streamlined so that new forest data can be modeled simply and with minimal expense. For future studies I do, however, encourage the testing of mineralizable nitrogen as a potentially valuable parameter for predicting forest productivity. I expect that as these models are tested and used, the boundaries that separate the nutrient regimes established in this study will be redefined and improved.

An important practical application of this thesis is the correlation of the nutrient regimes to field identifiable traits. The two traits that were found useful in this way were root depth, as defined by CanSIS (Agriculture Canada 1982), and humus form. Both of these are simple to note in normal field surveys of a forest. The humus form alone cannot be the only indicator of these regimes, however, because in the site index modeling attempts humus form was not found to be a useful predictor. Thus, the inclusion of root depth is necessary. These field assessments will likely benefit from additional research that focuses on other field identifiable traits such as slope position, parent material, soil texture, coarse fragments content, soil colour, depth of horizons, and type of horizons.

This information could be carried into the forest as part of a field manual to identify the soil nutrient regimes (Figure 4-1). The following is an example of how this might work with root depth and humus form in an aspen hardwood forest: In a freshly excavated soil pit the effective rooting depth is measured; if it is less than 25 cm then the site is rich or very rich, if it is greater than 25 cm the site is medium, poor, or very poor. The moder humus form has been correlated with very rich sites and the connection between humimor and very poor sites merits further investigation. For an example a soil with a root depth of 40 cm and the humus form is a humimor, it is likely a very poor soil nutrient regime. If the root depth is 20 cm and the humus form is a fibrimor the nutrient regime is likely rich, but if the 20 cm rooting depth was paired with a modor humus form the nutrient regime would be very rich. This assessment could be done at the same time that the field staff assess soil moisture regime and depth of horizons. The shortcoming of this is that so far there are only two characteristics for identifying the regimes. More characteristics need to be determined for this to become a more reliable and effective field tool. This key still needs work as a significant number of soils can be misclassified (Table 4-1).

The classification of the SNRs using laboratory data in cluster analysis and discriminant analysis was compared to SNRs determined from field information. This comparison was done by producing a contingency table of the number of cases that would be

classified by each method (Table 4-1). Percent correctly classified was produced by assuming that in each direction on the table that the highlighted method yielded the correct determination of SNRs and therefore equalled one hundred percent. In Table 4-1 the laboratory data can be used to establish the SNRs with an average accuracy of 67% relative to the field determined SNRs. Comparing the reverse there is an average acuracy of 57% correct when comparing field determined SNRs to the SNRs determined with the use of laboratory data. The very rich group was easily determined with either method with 75% to 100% being classified correctly. The very poor group was the most likely to be classified incorrectly with only 23% to 43% being classified correct. Based on these results there is much refining that needs to be done to enable field staff to correctly differentiate between the groups. The addition of more field identifiable traits would be desirable to improve the key.

Once the field data is collected, including the soil nutrient regime, the data could be stratified by parent material. Properties such as nutrient regime and moisture regime can then be used to predict site index for a soil. This may be estimated even if there are no trees present at the plot as long as the soil properties can be properly assessed. The productivity of a soil may not be completely determined if a characteristic such as humus form is not present and the key for determining needs this information. This is another reason that more field-identifiable traits need to be correlated to soil nutrient regimes to strengthen this connection.

To make this information more useful to other regions similar work should be done across the boreal plains. Ideally, this will produce nutrient regimes that can be applied to forests in Manitoba, Saskatchewan, and Alberta. There is already some use of a similar key in western Alberta and Saskatchewan (Beckingham *et al.* 1996a, Beckingham *et al.* 1996b) that could be used in conjunction with this information to create a key that can work across the western boreal forest. However, because these keys are based on work done in British Columbia, extrapolations to the boreal plain should be made with caution.

4.1. References

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Courtin, P.J., Klinka, K., Feller, M.C. and Demaerschalk, J.P. 1988. An approach to quantitative classification of nutrient regimes of forest soils. Canadian Journal of Botany. **66**: 2640-2653.

Klinka, K., Wang, Q. and Kayahara, G.J. 1994. Quantitative characterization of nutrient regimes in some boreal forest soils. Canadian Journal of Soil Science. **74**: 29-38.

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Table 4-1. Contingency table of the soil nutrient regimes (SNRs) derived from the laboratory data versus the SNRs derived from the field properties using the flow chart in Figure 4-1. For the V5 (aspen hardwood) plant community.

	SNRs (number of plots)					
Field SNRs (number of plots)	**VP**	**P and M**	**R**	**VR**	**Total**	**% correctly classified by field SNRs**
VP	3	4	0	0	7	43
P and M	10	24	0	0	34	71
R	0	3	2	0	5	40
VR	0	0	1	3	4	75
Total	13	31	3	3	50	57*
% correctly classified by lab SNRs	23	77	67	100	67*	64*

VP = very poor, P = poor, M = medium, R = rich, VR = very rich; *average

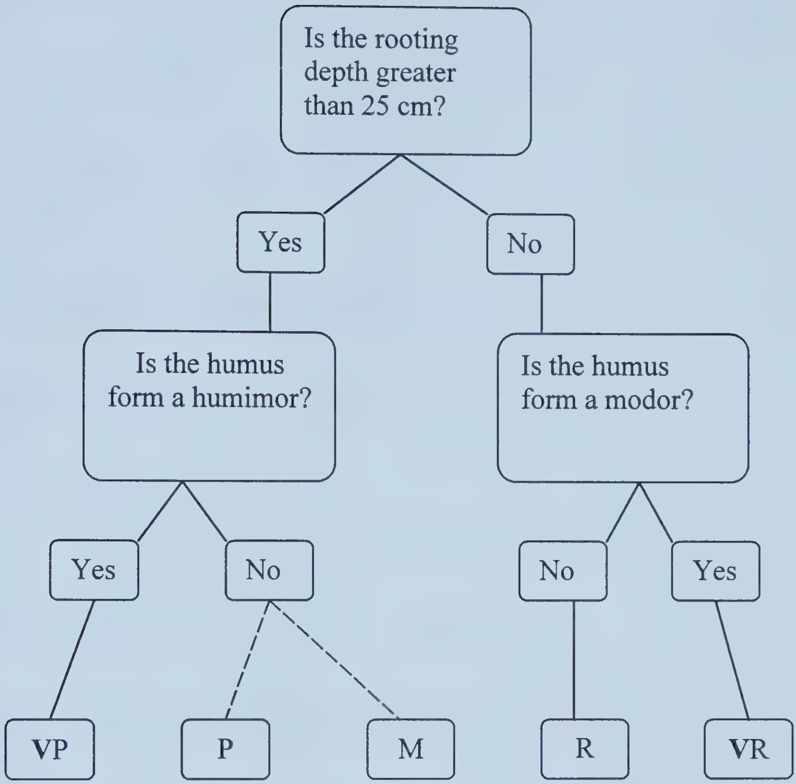


Figure 4-1. Proposed flow chart for determining soil nutrient regimes in the field. Soil Nutrient Regimes: VP=very poor, P=poor, M=medium, R=rich, VR=very rich.

Appendix A

SNR classification model:

$f = a + bx_1 + cx_2 + dx_1x_2 + ex_1^2 + gx_2^2$
x_1= FFDM (kg m^{-2})
x_2= C:N surface mineral

Group VP discriminant function coefficients
a= -75.056 b= 2.504 c= 9.181 d= -0.028 e= -0.073 g= -0.344

Group P discriminant function coefficients
a= -49.749 b= 1.675 c= 8.008 d= -0.014 e= -0.097 g= -0.379

Group M discriminant function coefficients
a= -70.125 b= 2.146 c= 11.894 d= 0.075 e= -0.143 g= -0.746

Group R discriminant function coefficients
a= -80.963 b= 2.968 c= 9.134 d= -0.037 e= -0.05 g= -0.383

Group VR discriminant function coefficients
a= -67.37 b= 1.297 c= 7.7 d= 0.15 e= -0.069 g= -0.792

To use: insert new values for the individual plot into the model along with the coefficients of the groups. Repeat for each group. The discriminant function that yields the largest value determines the group for the new plot.

Appendix B

Site index example calculation:

The example plot has three site trees sampled: 1= 98 years, 24.5m; 2= 91 years, 24.5m; 3= 90 years, 22.6m.

Tree one: age 98 years, height-1.3= 24.5m-1.3m= 23.2m
Use age 50 years for prediction age ($t = 50$) to get site index at 50 years.
The coefficients, prediction age, the recorded age at breast height, and adjusted height were put into the model. Due to the length of this equation the coefficient for "*b*" could not be demonstrated in this formula. The coefficient is: *b*= 1360.651

$$H_1 = \left[\frac{\left(23.2 + \left[b/50^{1.185685}\right] + \sqrt{\left(23.2 - \left[b/50^{1.185685}\right]\right)^2 + 4b(23.2)/98^{1.185685}}\right)}{2 + \left(\dfrac{4b/50^{1.185685}}{23.2 - \left[b/50^{1.185685}\right] + \sqrt{\left(23.2 - \left[b/50^{1.185685}\right]\right)^2 + 4b(23.2)/98^{1.185685}}} \right)} \right] + 1.3$$

$$H_1 = 20.29m$$

The other two height estimates for age fifty years were:

$$H_2 = 20.78m$$
$$H_3 = 19.07m$$

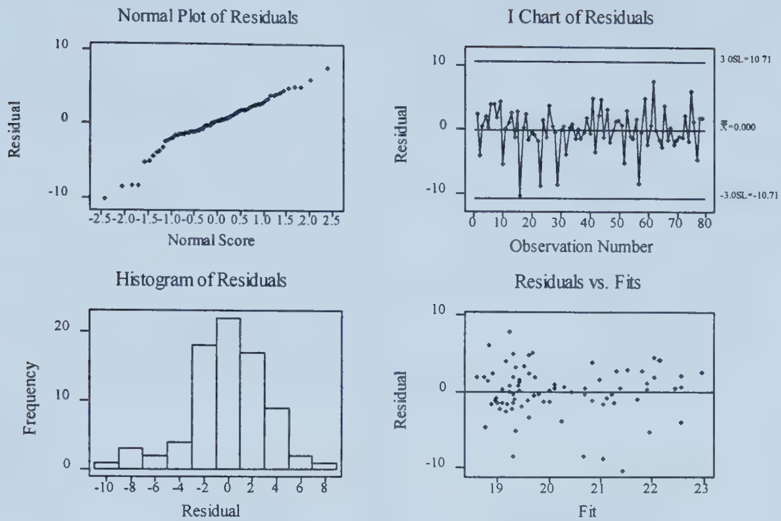
The average of these three height predictions is:

$$SI_{Aspen} = {(H_1 + H_2 + H_3)}/{3} = {(20.29m + 20.78m + 19.07m)}/{3}$$
$$SI_{Aspen} = 20.05m$$

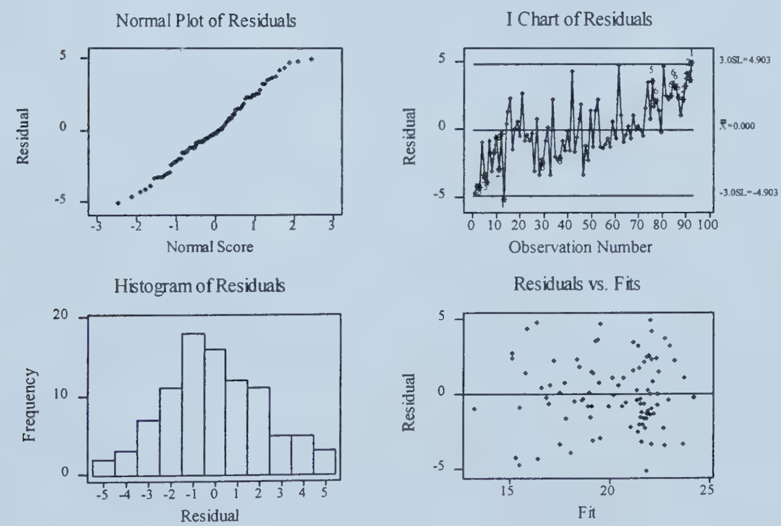
The site index for aspen at this example plot is 20.05m.

Appendix C

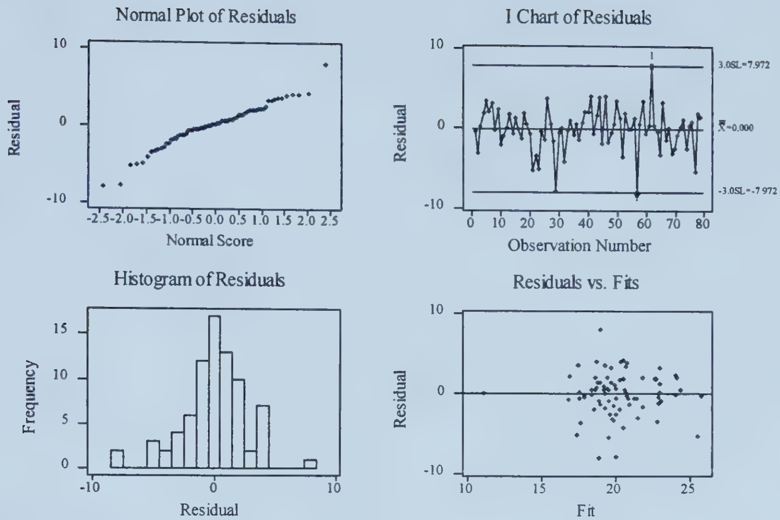
Residual plots for models 2-15:



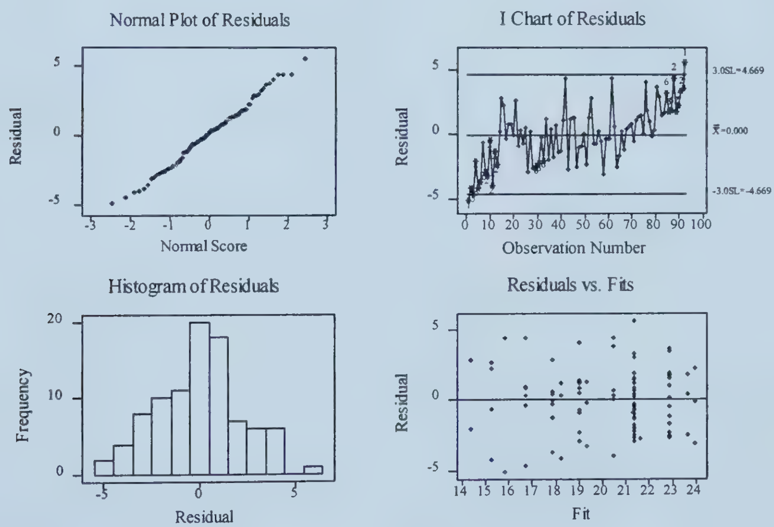
Equation 2



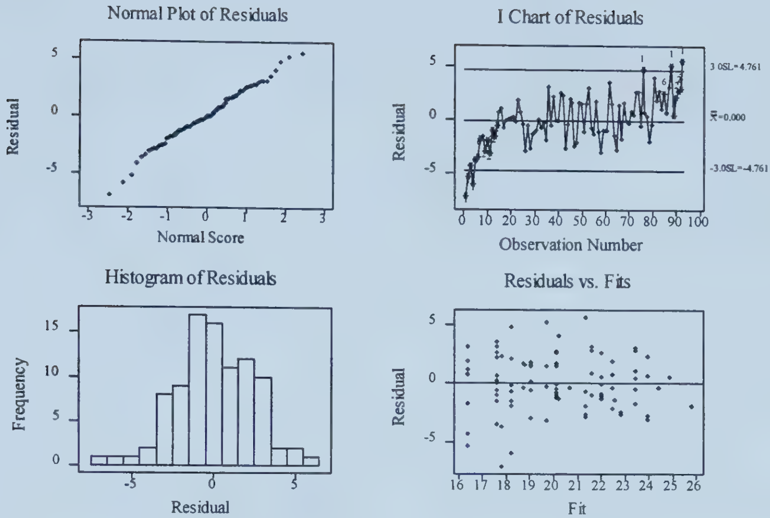
Equation 3



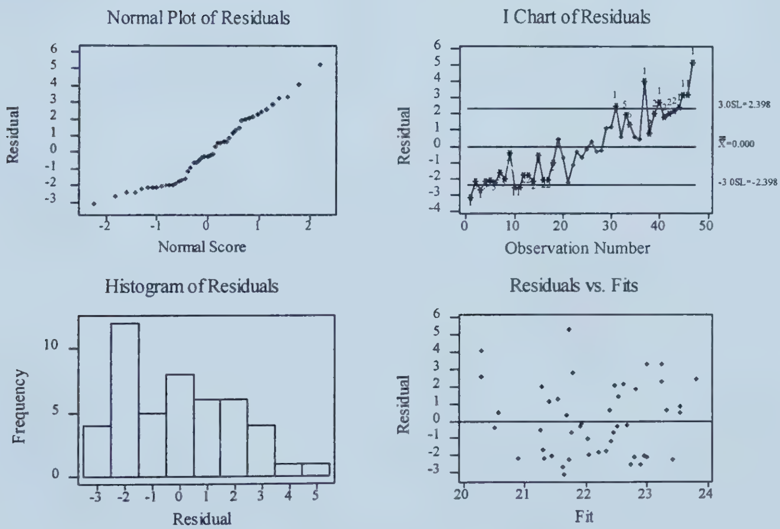
Equation 4



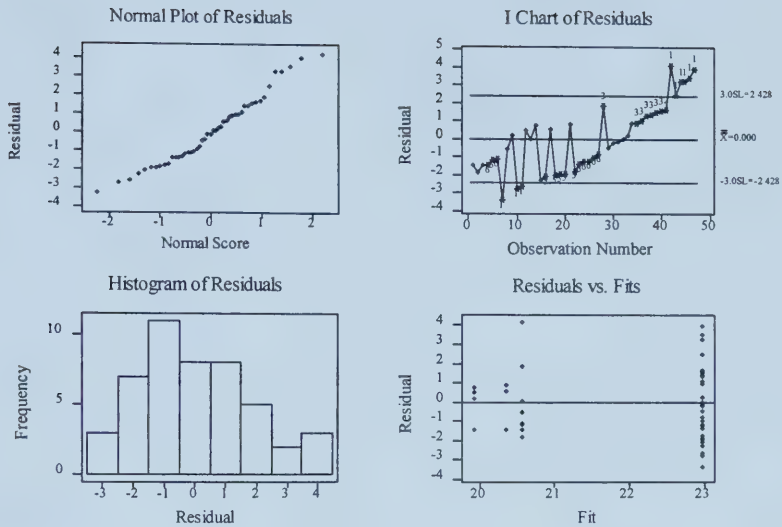
Equation 5



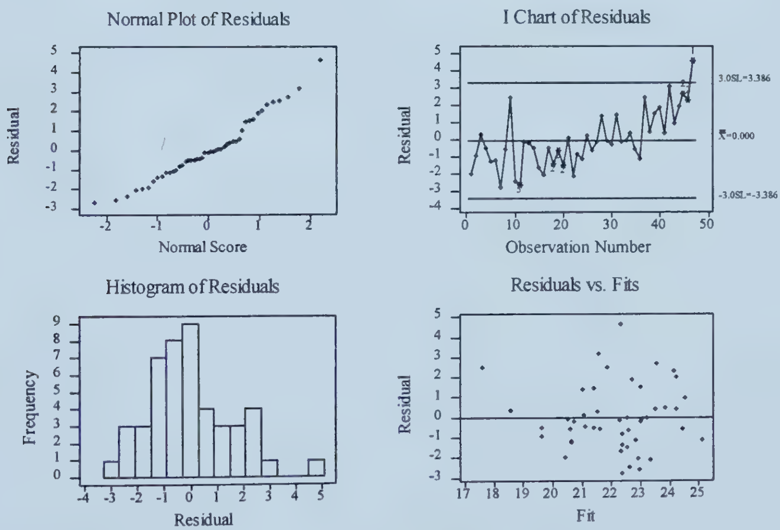
Equation 6



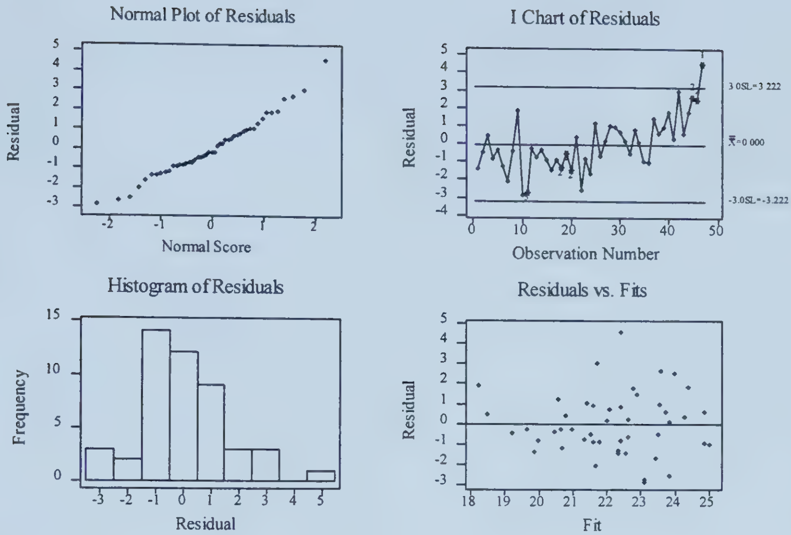
Equation 7



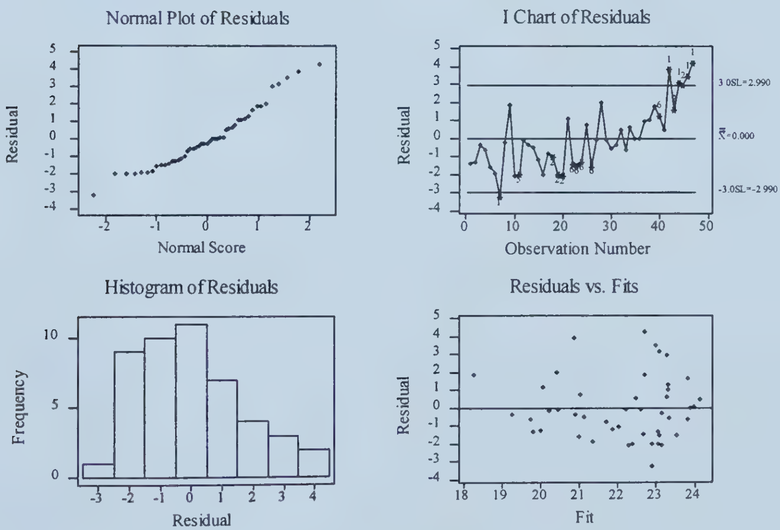
Equation 8



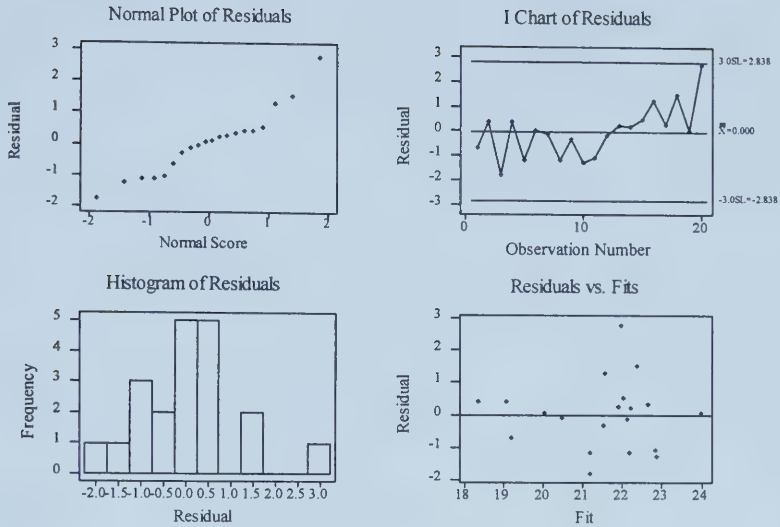
Equation 9



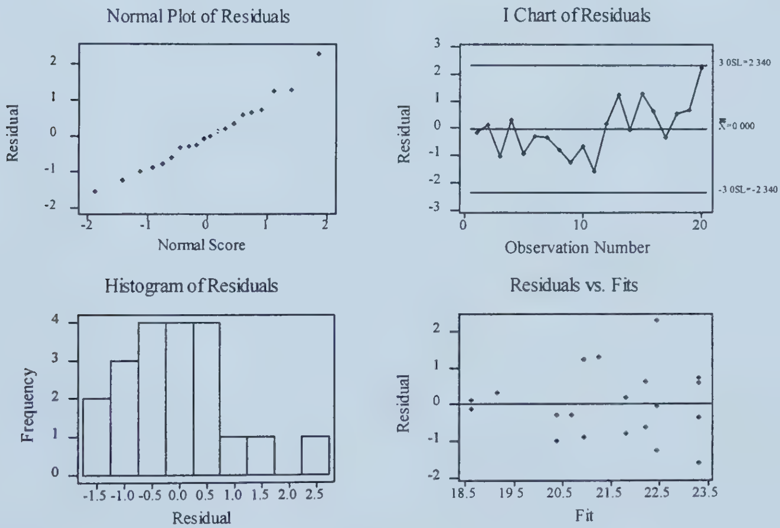
Equation 10



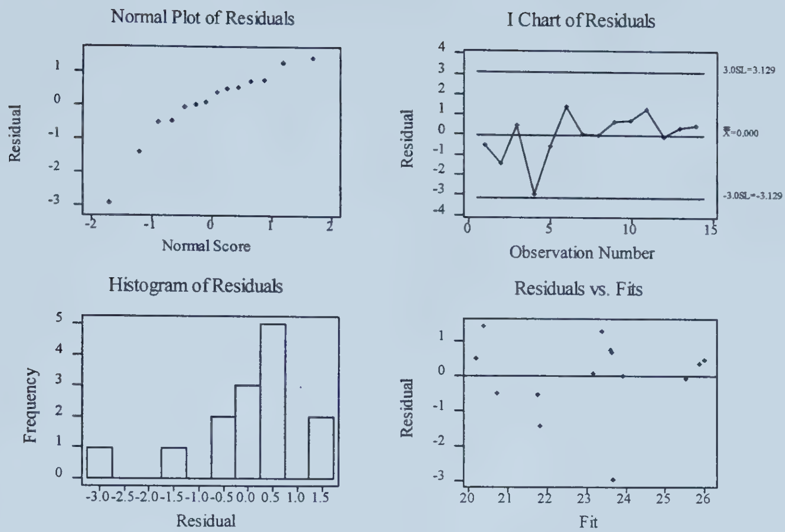
Equation 11



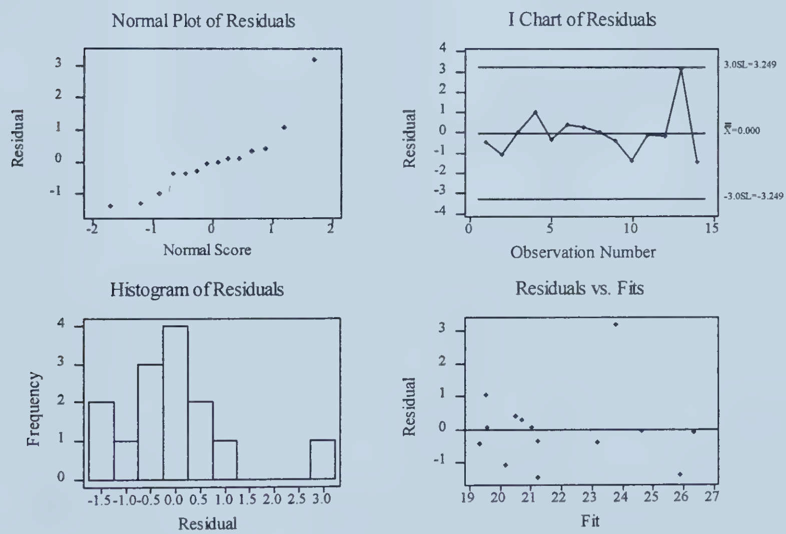
Equation 12



Equation 13



Equation 14



Equation 15